SCHOOL OF CELTIC STUDIES

# ANNUAL REPORT (PART 2) 2011

Annual Report of the Governing Board of the School of Celtic Studies for the year ending 31 December 2011.

**Bord Rialúcháin Scoil an Léinn Cheiltigh / Governing Board of the School of Celtic Studies**
The Board met twice during the year, on 9 June and 17 November.
Professor Anders Ahlqvist (*Chairman*); Professor Máire Herbert; Professor Jim McCloskey; Dr Uáitéar Mac Gearailt; Dr Eilís Ní Dheá; Dr Máire Ní Mhaonaigh; Professor Ailbhe Ó Corráin; Professor Ruairí Ó hUiginn; Dr Nollaig Ó Muraíle; Dr Katharine Simms; Professor Liam Breatnach; Professor Pádraig A. Breatnach (*Director*); Professor Fergus Kelly.

**Foireann agus Scoláirí / Staff and Scholars**
*Senior Professors*: Pádraig A. Breatnach (Director), Liam Breatnach, Fergus Kelly
*Professors*: Malachy McKenna, Pádraig Ó Macháin
*Assistant Professors*: Aoibheann Nic Dhonnchadha, Michelle O Riordan (Publications Officer)
*Bibliographer*: Alexandre Guilarte
*Dialectologist*: Brian Ó Curnáin
*Bergin Fellow*: Clodagh Downey (to 1 August 2011)
*O'Donovan Scholars*: Nora White (to 30 November 2011), Sorcha Nic Lochlainn (from 1 October 2011), Eoin O'Flynn (to 30 September 2011), Anna Matheson, Helen Imhoff .
*Librarian*: Margaret Kelly (Irons)
*Library Assistant*: Órla Ní Chanainn
*School Administrator*: Eibhlín Nic Dhonncha
*Technical Staff*: Anne Marie O'Brien (ISOS)
*IT support*: Andrew McCarthy (part-time), Stephen McCullagh (part-time)
*IRCHSS Postdoctoral Fellow* (from 1 October 2011): Roisin McLaughlin

## 1.1 TAIGHDE/RESEARCH

**Canúneolaíocht / Dialect studies**
*Malachy McKenna* continued work on *The Irish of Rann na Feirste: a phonemic study* (forthcoming) and revised a draft of the phonemic inventory, describing in detail and comprehensively the phonemic realisations. Work continued also on devising a set of descriptors on which to base the discussion of the articulatory gestures employed in the production of phonetic segments. A number of fieldtrips were made to Rann na Feirste to elicit specific information on the phonemic inventory, and to maintain contact with consultants on whose co-operation the whole project depends. Other research involved the revision of his Summer School coursebook, viz. *Linguistic Introduction to Modern Irish*, along with an updating of the audio material that accompanies the coursebook. He collaborated with Orit Eshel of the Hebrew University of Jerusalem on a systemic-functional analysis of copular clauses in the spoken Irish of Co. Donegal.
*Brian Ó Curnáin* was engaged on research for his monograph on the dialect of East Galway (Achréidh na Gaillimhe) preparing notes on phonetics, phonology, accidence, syntax and vocabulary. He transcribed speech recordings of the Irish of Conamara, Dúiche Sheoigheach, and Achréidh na Gaillimhe, and transferred field-recordings to hard-disk codifying the metadata paying special attention to phonemic analysis and the role of nasalisation, sandhi, vocalic continuation (through **/h/**) word-stress, vocabulary etc. He also worked on language contact, death of languages, language acquisition and bilingualism.

**Saothair eagarthóireachta, critic théacsúil etc. / Editions and textual criticism, etc.**
*Liam Breatnach* continued with his edition of the Old Irish law tract *Córus Bésgnai*, and worked on

the *Grammar of Middle Irish.* Editions of poems by Dubhthach Óg Ó Duibhgeannáin and Eochaidh Ó hEódhusa were progressed by *P. A. Breatnach* who also collected and edited materials for the continuing series 'Togha na hÉigse' (previously unpublished 18th century Munster poetry). He resumed work on the introduction to his edition of *Airdena na cóic lá ndéc ria mbráth*, and researched a contribution on the topic 'Múnlaí seanamhrán i ndánta Aogáin Uí Raithile' for presentation at a conference at UCD (May). *Fergus Kelly* continued with his edition of the Legal Treatise attributed to Giolla na Naomh Mac Aodhagáin (*Corpus Iuris Hibernici* ii 691.1-699.4). He worked also on his edition of an Old Irish text on legal disputes within marriage for *Celtica* 27 (*Corpus Iuris Hibernici* i 144.5–150.16). *Pádraig Ó Macháin* conducted research on the unpublished poetry of Fearghal Óg Mac an Bhaird, particularly on the early poetry as found in National Library of Scotland MS Adv. 72.2.14 and in Leabhar Clainne Suibhne (RIA MS 475 (24 P 25)); this work dovetailed with ongoing investigation into the composition of the later bardic *duanaireadha.* Research was continued by *Clodagh Downey* as part of her project to edit and translate the poetic corpus of the Middle-Irish poet Cúán ua Lothcháin. This included consultation of manuscripts, collating transcripts, translation of the poetry, commentary on linguistic features, documentation of the historical content of the poetry and of the historical context in which it was written, and analysis of other literary aspects such as metre and style.

*Helen Imhoff* continued to prepare an edition of *Fástini Airt meic Cuind*, researching the historical background, and carried out some work on *Aided Chonchobair*. Work on the 'Parsed Old and Middle Irish Corpus', was continued by *Elliot Lash* which involved tagging and parsing texts automatically and implementing manual checks as well as dating of the texts used in the corpus. He also conducted research on the use of analogy vs. reanalysis in understanding linguistic change, particularly with regard to some issues in the history of the Irish language, and researched various approaches to degrammaticalization, in order to apply some of the theories of degrammaticalization to the history of the Irish 'ro' particle. *Anna Matheson* prepared two articles on the medieval Irish legal material concerning persons of unsound mind, viz. 'On the structure of the Old Irish Legal text *Do drúthaibh 7 meraibh 7 dasachtaibh* and on the terms *cáepthae* and *finelach* therein', and 'The terms *drúth go rath* and *mer gin rath* in early Irish legal scholia'. *Sorcha Nic Lochlainn* worked on a collection of Gaelic songs with accompanying essays, provisionally entitled 'Cross-currents in Song'. *Roisin McLaughlin* continued the edition of *Mittelirische Verslehren III* and *In Lebor Ollaman* as part of a project for IRCHSS Post-doctoral Fellowship. She also prepared editions of a Middle Irish text on almsgiving in the *Leabhar Breac* and RIA MS 3 B 23, and a text on judges and poets in the pseudo-historical prologue to the *Seanchas Már*.

**Staidéir lámhscríbhinní / Manuscript studies**

*P. A. Breatnach* continued research for chapters of *The Four Masters and their manuscripts* (forthcoming), including preparation of a chronological inventory of the manuscripts of Cú Coigcríche Ó Cléirigh, based on palaeographical and text-critical criteria. He worked also on the catalogue of Irish manuscripts in Brussels and researched aspects of the development of cursive handwriting in Irish for presentation at a conference in Paris and an account of the history of Irish handwriting in the seventeenth century for presentation at the XIV International Congress of Celtic Studies at Maynooth. *Aoibheann Nic Dhonnchadha* completed catalogue descriptions of a number of important Irish medical manuscripts in the Library of Trinity College, Dublin, dating from the fifteenth and sixteenth centuries (nos. 1314/4, 1319/2/6, 1315, 1341, 1435, 1436). *Pádraig Ó Macháin* conducted research on a number of Irish manuscripts connected with projects involving ISOS (see below). This included providing a description of a manuscript in Farmleigh House known as 'Elizabeth's Irish Primer' which was subsequently published on the ISOS project website. He also researched the relationship of this manuscript with another volume known as the Nugent poem-book (National Library of Ireland, MS G 992), and the results of this study are due for publication in 2012. Research undertaken into the important fifteenth-century manuscript known as the Book of Lismore in connection with the exhibition of the manuscript which was held in University College Cork, from July to October, is noticed below (1.2).

**Stair liteartha agus chultúrtha / Literary and cultural history**

*Michelle O Riordan* continued work on a book-length study of seventeenth-century Irish political poetry and its cultural context. Irish identities brought into relief under the pressure of the 1641 rebellion and in the period of Cromwell's interregnum showed themselves to be many-sided and mutable. This work will revisit some short-hand terms of reference that allow coherent discussion of the frenetic years of the Irish Catholic Confederacy.

*Eoin O'Flynn* completed his thesis entitled 'The organisation and operation of Uí Neill kingship in the Irish midlands: Clann Cholmáin c. 550-916' (September). Specific issues examined include: (i) how the kingship of Mide and the delegation of kingly title was used by Clann Cholmáin dynasts to secure and consolidate political support in the midlands; (ii) Clann Cholmáin's response to the initial appearance of Vikings in the midlands and subsequent development of periodic alliances with the kings of Dublin; (iii) the nature of the various 'disturbances' recorded at Óenach Tailten in which Clann Cholmáin were often involved.

**1.2 Meamram Páipéar Ríomhaire / Irish Script on Screen (ISOS)**

Two projects were brought to completion under ISOS project-director Pádraig Ó Macháin in January, viz. the display, with catalogue descriptions by Professor Ó Macháin, of three Irish manuscripts in the holding of the State Library of Victoria; and a pilot project undertaken with University College Cork to digitize five Irish manuscripts from their collection, and to display them together with catalogue descriptions provided by Professor Breandán Ó Conchúir. Following the successful completion of the UCC pilot project, agreement was reached with Special Collections, Boole Library, UCC, that the digitization of their Irish manuscripts should continue. Accordingly MS 1 (a manuscript written by Seán Ó Cléirigh) was digitized and displayed on the ISOS project website during the year. It is intended that more UCC material will be digitized and added to the ISOS site in the future.

Other collaboration with UCC involved the digitization by ISOS/School of Celtic Studies of the fifteenth-century manuscript known as the Book of Lismore. This digitization was undertaken at Chatsworth House, Derbyshire, as part of the preparations for the display of the manuscript at Glucksman Gallery, UCC from July to October. The digitized images were used in informational- and publicity-material associated with the exhibition, and in a touch-screen presentation of pages from the Book, written and prepared by Pádraig Ó Macháin. It is intended that the Book of Lismore will be available on the ISOS website in due course.

The processing and display of manuscripts from National Library of Scotland continued, with ten manuscripts being added to the collection.

Further digitization work was carried out at University College Dublin, and at the Royal Irish Academy. Four manuscripts from the Franciscan collection were digitized (A7, A15, A18, and A23). Five manuscripts were digitized at the RIA (MS 3 C 19, C iv 2, 23 O 4, 23 P 26, 23 D 14).

A new collaboration was entered into with the digitization by ISOS of the sixteenth-century Irish primer ('Elizabeth's Irish Primer') at Farmleigh House. This primer was written *c*. 1563 by Christopher Nugent, Baron Delvin, and had never before been reproduced in its entirety in any format. A description of the manuscript was made by Pádraig Ó Macháin and both manuscript and description were displayed on ISOS. The ISOS images were later used by Farmleigh for the creation of a facsimile of the Primer for presentation to the President of Ireland and to the Queen of England during the state visit of 2011.

**1.2 An Tionscnamh Bibleagrafaíochta/Bibliography Project**

Alexandre Guilarte continued work on the compilation of the *Bibliography of Irish Linguistics and Literature*, locating, describing and analysing research published on medieval and modern Irish philology, including material from the following national and international learned journals: *Béaloideas* (vols. 39-41); *Irish Historical Studies* (vols. 18-69), *Lingua* (from vol. 29), *Münchener Studien zur Sprachwissenschaft* (from vol. 30); *Studia Celtica Japonica* (1st ser., from vol. 1). He

continued to maintain the public website of the bibliography project eBILL, http://bill.celt.dias.ie.

### 1.3 Ogham-3D

The project is supported by an expert advisory panel consisting of Professors Fergus Kelly, Werner Nahm (Director of the School of Theoretical Physics, DIAS), Damian McManus (TCD) and Fionnbarr Moore (National Monuments Service, Department of Arts Culture and the Gaeltacht). Project researcher Nora White continued work on researching Ogham stones for individual records in database. She also progressed the scanning of stones in the National Museum of Ireland and on-site in Wicklow and Kildare. She has prepared a website for activation in April 2012. The project benefited from the assistance of David Fitzpatrick through the offices of the Workplacement Programme (WPP) (FÁS) from (April 2011-January 2012).

### 1.4 Tionscnamh *Leabhar Breac* / *Leabhar Breac* Project

Liam Breatnach continued to direct the preparation of a diplomatic edition of the *Leabhar Breac*, with the involvement of the Bergin Fellows and Scholars. Roisin McLaughlin transcribed two Latin-Irish texts as part of the project.

### 1.5 Eagarthóireacht irisí léannta agus leabhar / Editing of learned journals and books

Liam Breatnach: Co-editor of *Ériu*, volume LXI (Royal Irish Academy). Continued editorial work on the edition of *Collectio Canonum Hibernensis* submitted by Dr Roy Flechner.
Pádraig A. Breatnach: Co-editor of *Celtica*, vol. 27 (for publication 2012).
Fergus Kelly: Co-editor of *Celtica* 27 (for publication 2012). Also edited *The cult of the sacred centre* by †Proinsias Mac Cana (launched July 2011).

### 1.6 Foilsitheoireacht / Publishing

The publications committee of the School of Celtic Studies met on three occasions (chairman L. Breatnach; secretary M. O Riordan, Publications Officer).

***New publication***

The committee oversaw the publication edited by F. Kelly of the following publication: †Proinsias Mac Cana, *The Cult of the Sacred Centre: Essays on Celtic Ideology,* viii + 344pp.
ISBN 978-1-85500-219-7

*Athchlónna / Reprints*

The following reprints were seen through the press by Michelle O Riordan, Publications Officer, and Eibhlín Nic Dhonncha, Administrator:
Cainneach Ó Maonaigh, O.F.M. *Seanmónta Chuige Uladh*
ISBN 978-1- 85500-069-8
Kuno Meyer, *Death-Tales of the Ulster Heroes*
ISBN 978-1-85500-171-8
Eleanor Knott, *Irish Syllabic Poetry 1200-1600*
ISBN 978-1-85500-048-3
Fergus Kelly, *A Guide to Irish Law*
ISBN 978-1-85500-214-2
Ludwig Bieler, *The Irish Penitentials*
ISBN 978-1-85500-066-7
Tomás de Bhaldraithe, *Gaeilge Chois Fhairrge: an Deilbhíocht*
ISBN 978-1-85500-029-2
J. J. Tierney, *Dicuili Liber de Mensura Orbis Terrae*
ISBN 978-1-85500-079-7
Brian Ó Cuív, *Cnósach Focal ó Bhaile Bhuirne i gCunndae Chorcaí.*

ISBN 978 -1- 85500-024-7
Maud Joynt, *Tromdámh Guaire*
ISBN 978-1-85500-220-3

### 1.7 Díolachán Leabhar/Sale of books

The promotion of School publications was conducted by the School Administrator, Eibhlín Nic Dhonncha, through advertising on the School website and in the following outlets: *Books Ireland*; *National Concert Hall Annual Brochure*; *Comhar*; *Saol*; *Foinse*; *Conradh na Gaeilge: Clár Seachtain na Gaeilge*; *An tOireachtas: Clár na Féile*; *Lámhleabhar An Choláiste Ollscoile Baile Átha Cliath*; *Library News.*

### 1.8 Foilseacháin na foirne / Staff publications

*Liam Breatnach*:

- 'Saint Patrick's oath', in Anders Ahlqvist and Pamela O'Neill (eds) *Language and power in the Celtic world. Papers from the seventh Australian conference of Celtic Studies. The University of Sydney, September-October 2010* (Sydney 2011) 13-35.
- *The Early Irish Law Text Senchas Már and the Question of its Date*, E.C. Quiggin Memorial Lectures, 13 (Cambridge 2011), 48pp.

*Alexandre Guilarte*:

- Contributed entries on Celtic Studies publications to *International Medieval Bibliography* 44:2 (July – December), 45:1 (January-June), Institute for Medieval Studies, University of Leeds

*Fergus Kelly*:

- 'The place of women in Early Irish Society, with special reference to the Law of Marriage', Anders Ahlqvist and Pamela O'Neill (eds), *Language and power in the Celtic world. Papers from the seventh Australian conference of Celtic Studies. The University of Sydney, September-October 2010* (Sydney 2011), 159-79.
- 'The Recovery of Stolen Property: Notes on Legal Procedure in Gaelic Ireland, Scotland and the Isle of Man', in Fiona Edmonds and Paul Russell (eds), *Tome: Studies in Medieval Celtic History and Law in honour of Thomas Charles-Edwards* (The Boydell Press, Woodbridge 2011) 165-71.

*Malachy McKenna*:

- '*Is there vowel harmony in Irish and Scottish Gaelic*?' in Anders Ahlqvist and Pamela O'Neill (eds), *Language and power in the Celtic world. Papers from the seventh Australian conference of Celtic Studies. The University of Sydney, September-October 2010* (Sydney 2011) **PAGES**

*Brian Ó Curnáin*:

- 'An Chanúineolaíocht' in Máire Ní Neachtain agus Tadhg Ó hIfearnáin (eag.), *An tSochtheangeolaíocht: Feidhm agus Tuairisc* (Cois Life, 2011) 83-110.
- 'An Ghaeilge Iarthraidisiúnta agus an Phragmataic Chódmheasctha Thiar agus Theas' in Ciarán Lenoach, Conchúr Ó Giollagáin, Brian Ó Curnáin (eag.), *An Chonair Chaoch: an Mionteangachas sa Dátheangachas* (Leabhar Breac, 2012) 284-364.

*Pádraig Ó Macháin*:

- 'Observations on the manuscript of Tadhg Ó Cianáin', in Fearghus Ó Fearghail (ed.), *Tadhg Ó Cianáin*: *an Irish scholar in Rome* (Dublin 2011) 171-205.
- (with Fearghus Ó Fearghail) 'A nineteenth-century transcript of Ó Cianáin's manuscript', in Fearghus Ó Fearghail, *Tadhg Ó Cianáin: an Irish scholar in Rome* (Dublin 2011) 206-14
- 'Dan le Pádraig Denn', *An Linn Bhuí* (2011) 139-44.

*Michelle O Riordan*:

- '*Cuallacht Léannta*, - an account of the three scholars P. Ua Duinnín, E. Mac Fhir Leinn, L. Mac Cionnaith' in *Timire an Chroí Ró-naofa: Comóradh 100 bliain an Timire 1911-2011*, pp.15-25.

## 1.8 Leabharlann/Library

Current and retrospective cataloguing continued. Acquisitions continued in subject areas relevant to the research needs of the School. Regular updates on recent accessions and current periodicals (both print and online) were issued. Research and bibliographical queries from members of the School were dealt with. Inter library loans were ordered, consulted and returned to the lending institution. The Library Committee met in February, June and October to advise on library policies, promotion of the library and development and implementation of strategic changes.

Margaret Irons continued as committee member of the Academic and Special Libraries section of the Library Association of Ireland. The committee meet once a month and organise an Annual Seminar along with Informal Netwoking Evenings and Training Courses. Margaret Irons was involved in the organisation of a one day seminar entitled *Library Services – So What* which was hosted by the Academic and Special Libraries section of the LAI. The seminar was held on the February 2011 in the Radisson SAS Hotel, Dublin. She also attended the following seminars during the year: LIR, The Annual Seminar entitled *Ebooks: Caressing The Divine Details* which was held on the 25th March at the Davenport Hotel, Dublin. ANLTC (Academic and National Library Training Co-operative) course entitled *The Printed Word in Irish Hamanities Research* which was held in the Royal Irish Academy on 21st June.

The Summer School which was held from 18 – 30 July saw record numbers of visitors to the library. The library extended its opening hours to accommodate visiting students.

FÁS WPPI – The Workplacement Programme (WPP) is a Government supported programme that brings employers and unemployed together for a work experience placement. Jennifer Flynn gained nine months of cataloguing experience in the library under the FÁS WPP1 whilst cataloguing over 2,000 items for the retrospective cataloguing project. The retrospective cataloguing project is an ongoing library project to transfer card catalogue records to the library management system.

The library was re-carpeted and library windows were refurbished.

## 1.10 Imeachtaí/Events

### Scoil Shamhraidh / Summer School

The Summer School in Mediaeval and Modern Irish Language and Literature of the School of Celtic Studies was held on 18-29 July. The chairman of the Summer School Committee was L. Breatnach; organisation was by E. Nic Dhonncha. Courses offered were: Beginners Modern Irish (M. McKenna), Advanced Modern Irish (P. A. Breatnach), Intermediate Old Irish (C. Downey), Advanced Old Irish (L. Breatnach). Lecture-course topics were: 'Early Irish law and society' (F. Kelly), 'Early Irish Irish poets and satire' (R. McLaughlin), 'Irish mythological literature' (C. Downey), 'Metre and poetry in the Modern Irish accentual tradition' (P. A. Breatnach), 'Irish manuscript tradition' (P. Ó Macháin), 'Manuscripts and medical texts 1350-1650' (A. Nic Dhonnchadha). In all 46 students attended from 12 countries.

### XIV Comhdháil Idirnáisiúnta sa Léann Ceilteach / XIV International Congress of Celtic Studies

The Congress was organised by the School of Celtic Studies in conjunction with NUI Maynooth and Trinity College Dublin. The organising committee was as follows: L. Breatnach, School of Celtic Studies (Local President), K. Simms, TCD, D. McManus, TCD, R. Ó hUiginn, NUI Maynooth. Administrative assistance was given by E. Nic Dhonncha, and IT assistance by A. McCarthy. The Congress took place on the campus of NUI Maynooth 1-5 August. Registered delegates: 550; papers: 370; plenary lectures 9.

### Léacht Reachtúil / Statutory Public Lecture

This year's Statutory Public Lecture was given by Professor Liam Breatnach of the School of Celtic Studies, Dublin Institute for Advanced Studies at Trinity College, Dublin on Friday, 18 November, before an audience of approximately 180 people as part of the annual Tionól of the School of Celtic Studies.. Title: 'Poet and scholar: The education of the *fili* in early mediaeval Ireland'

**Tionól 2011**
The School's annual Tionól took place on 18 and 19 November 2011, organised by Professor Fergus Kelly and the School Administrator Eibhlín Nic Dhonncha. It attracted a very large attendance with numbers exceeding 100 on both days. Papers on various aspects of Celtic Studies were delivered by 20 speakers from the Sweden, Austria, Germany, England, Wales, and Ireland. The following is the list of speakers and papers:
Fangzhe Qui (University of Oxford): 'The legal context of *Echtra Fergusa maic Léti*'
Anna Matheson (School of Celtic Studies): 'On the terms *drúth go rath* and *mer gin rath* in Early Irish legal commentary'
Mícheál Briody (University of Helsinki) 'In ár Lazarusannaí ag imeacht: Campa Géibhinn an Churraigh agus Bunús *Cré na Cille'*
Bary Lewis (Centre for Advanced Welsh and Celtic Studies): 'Hagiographical links in late-medieval Welsh poems to saints'
Aaron Griffith (University of Vienna): 'The Milan Glosses database'
Pádraic Moran (National University of Ireland, Galway): 'The date of O'Mulconry's Glossary and its place in the Irish glossary tradition'
Paul Russell (University of Cambridge): 'Henry Bradshaw, Old Breton and the editing of glossed texts'
Fergus Kelly (School of Celtic Studies): 'Irish words and phrases in the English of Massbrook, Co. Mayo: notes from the 1960s'
Riitta Latvio (University of Helsinki): 'The world according the *neimed*: categorising space, people and legal procedures in early medieval Ireland'
Raymond Hickey (University of Duisburg and Essen): 'Irish Phonology: examining how contrast works'
Allessio Frenda, Elaine Uí Dhonnchadha, Pauline Welby (Trinity College, Dublin): 'Not missing the *bád*: a spoken language corpus of Irish'
Michael Clarke (National University of Ireland, Galway): 'The *Mythologies* of Fulgentius in the Irish reconstruction of pagan antiquity'
Máirín Ní Dhonnchadha (National University of Ireland, Galway): 'At the helm: some new light on early Irish monasticism'
Roisin McLaughlin (School of Celtic Studies): 'A text on judges and poets in the pseudo-historical prologue to the *Senchas Már*'
Caoimhín Breatnach (University College Dublin): 'The transmission of an abridged version of the Gospel of Nicodemus in Irish sources'
Patricia Kelly (University College Dublin): 'Cormac's Glossary: the Book of Uí Mhaine version'
Dan McCarthy (Trinity College, Dublin): 'The Ó Cléirigh compilation of the Martyrology of Donegal'
Niamh Whitfield (Freelance archaeologist): 'What was *findruine*?'

**Seiminéir / Seminars**
Liam Breatnach conducted a seminar on Early Irish Law and a seminar on Old and Middle Irish verse and prose texts. Pádraig A. Breatnach conducted a seminar on bardic poetry.

**1.11 Léachtaí (foireann agus scoláirí) / Lectures (staff and scholars)**
*Liam Breatnach*:

- 'Gráid na bhFilí in Éirinn Fadó' (St Patrick's College, Drumcondra, 9 March)
- 'The education of the poet in early mediaeval Ireland' (*Irish Studies Symposium* University

of Uppsala, 4 October)
- 'Daniel A. Binchy as a legal scholar' (One-day conference on 'UCD Lawyers and Public Life: 100 Years of Activism and Influence', Saturday, 12 November in Newman House, St Stephen's Green, Dublin, as part of the centenary year (2011-12) celebrations of the UCD School of Law)
- 'Poet and scholar: The education of the *fili* in early mediaeval Ireland' (Statutory Public Lecture of the School of Celtic Studies for 2011, TCD, 16 November)

*Pádraig A. Breatnach*:
- 'Book hand and cursive in later Irish manuscripts: a problematic distinction' (*5e rencontre internationale du séminaire permanent sur la cursivité*, Institut de recherche et d'histoire des textes (IRHT), Paris, 15 April)
- 'Múnlaí seanamhrán i ndánta Aogáin Uí Raithile' (Comhdháil *Sealbhú an Traidisiúin*, Institiúid na hÉireann don Léann Daonna (HII), An Coláiste Ollscoile, Baile Átha Cliath, 20 Bealtaine)
- 'Metre and poetry in the accentual tradition' (3 lectures, Summer School, School of Celtic Studies, 21-23 July) ;
- 'Irish handwriting in the seventeenth century', *An XIV Comhdháil Idirnáisiúnta sa Léann Ceilteach*, Maigh Nuad (Plenary Lecture) (4 August)
- 'The anatomy of Irish bardic eulogy: a critical reading of a poem of solicitation (c. 1600)' (*Irish Studies Symposium*, University of Uppsala (4 October).

*Clodagh Downey*:
- 'The life and work of Cúán ua Lothcháin, an eleventh-century poet' (Royal Society of Antiquaries of Ireland, Merrion Square, Dublin, 31 March)
- 'Who was Ailill Mosaulum?' (XIV International Congress of Celtic Studies, NUI Maynooth, 5 August)

*Fergus Kelly*:
- 'Farming before the Norman Invasion: the evidence of the law-texts' (Dublin University Early Irish Society, TCD, 22 February; An Cumann Staire, Ollscoil na hÉireann, Gaillimh, 23 Márta);
- 'Medical care in Early Irish Law' (Seminar on Regimes of Care in Medieval Ireland, held jointly by the Míchéal Ó Cléirigh Institute and the Centre for the History of Medicine in Ireland, University College Dublin, 9April)
- 'Early Irish Law and Society' (6 lectures, School of Celtic Studies Summer School, 18-23 July)
- 'The Status of Professional Women in Early Irish Law' (XIV International Conference of Celtic Studies, NUI Maynooth, 1 August)
- 'Irish words and phrases in the English of Massbrook, Co. Mayo: notes from the 1960s' (Tionól, School of Celtic Studies, 18 November)

*Pádraig Ó Macháin:*
- 'Gaelic sources for pre-Famine social history' (Dunhill Lecture Series, Co. Waterford, January)
- 'Irish medieval digital initiatives' (University College Cork, January)
- 'Gaelic exiles in Louvain in the early 17th century: their poetry and their books' (IASIL Conference, Leuven, July)
- 'Litríocht na Gaeilge i gceantar an Chomaraigh' (Tionól an Fhómhair, Comhairle Chontae Phort Láirge, Meán Fómhair)
- 'The Book of Lismore' (Glucksman Gallery, UCC, 11 October)

- ‘Scribal features of the Book of Lismore’ (Book of Lismore Colloquium, Department of Irish, UCC, 22 October)
- ‘The writing of the Book of Lismore’ (Lismore Castle, 25 October)

*Aoibheann Nic Dhonnchadha:*

- ‘Léann Ghailéin i dtéacsanna leighis na Gaeilge, 1350-1650’. (TCD Colloquium on ‘Galen c.129-200 AD, in the Greek, Arabic, Jewish, Renaissance and Gaelic worlds’, Edward Worth Library, Dr Steevens’ Hospital, Dublin, 15 June)
- ‘The vocabulary of the “Almusór”, an Irish treatise on general pathology composed in 1400’ (Progress in Medieval Irish Lexicography, Dept. of Irish, Queen’s University Belfast (16 September)
- ‘The Book of Lismore: The Ó Callanáin connection and medical texts associated with the family’ (Book of Lismore Colloquium, Department of Irish, UCC, 22 October)
- ‘Medical Manuscripts and Texts, 1350-1650: Part 1, Historical Background’ (School of Celtic Studies Summer School in Medieval and Modern Irish Language and Literature, July).
- ‘Medical Manuscripts and Texts, 1350-1650: Part 2, Texts’ (School of Celtic Studies Summer School in Medieval and Modern Irish Language and Literature (July).

*Brian Ó Curnáin:*

- ‘L’irlandais de Iorras Aithneach, Co. Galway’ (*Séminaire de la Bretagne Linguistique,* Centre de recherches bretonnes et celtiques, Université de Bretagne Occidentale, Brest, 3 December);
- ‘Extrapolating from the Irish condition: aspects of demography and discourse in bilingual minority language communities’ (Conference on ‘Languages of the wider world: Understanding resilience and shift in regional and minority languages’, School of Oriental and African Studies, London University, and Fryske Akademy (Leeuwarden), Leeuwarden, Netherlands, 6-8 April);
- ‘Tógáil chlainne sa mhionteanga’ (Scoil Earraigh ‘Pleanáil Teanga’, Ollscoil na hÉireann, Gaillimh, eagraithe ag Acadamh na hOllscolaíochta Gaeilge, 28 Márta).

*Roisin McLaughlin*:

- ‘Poets and Satire in Early Ireland’ (3 Lectures, Summer School in Mediaeval and Modern Irish Language and Literature, School of Celtic Studies, July)
- ‘A Middle Irish Text on Almsgiving in the *Leabhar Breac* and RIA MS 3 23’ (XIV International Conference of Celtic Studies, Maynooth, August)
- ‘Rarely Attested Words in a Middle-Irish Metrical Tract’ (Progress in Medieval Lexicography Conference, Queens University Belfast, invited speaker, September)
- ‘A Text on Judges and Poets in the Pseudo-historical Prologue to the *Seanchas Már’* (*Tionól* School of Celtic Studies, November)

*Alexandre Guilarte:*

- ‘The Progress of BILL’ (XIV International Congress of Celtic Studies, NUI Maynooth, 1-5 August)

*Anna Matheson*:

- ‘The herring as buffoon in the folktale *Am peata sgadain*’. The Celts in the Americas Conference. St. Francis Xavier University, Nova Scotia. 29 June – 2 July 2011. (via skype)
- ‘Throwing clods at the insane and/or undesirable in Early Irish sources: a study of the *Cáepthae* “Clodded One”’ (XIV International Congress of Celtic Studies. National

University of Ireland, Maynooth, 1-5 August 2011)
- 'On the Terms *Drúth go Rath* and *Mer gin Rath* in Early Irish legal commentary' (*Tionól*, School of Celtic Studies, DIAS, 18-19 November)
- 'On the *Druth go Rath, the Mer gin Rath*, and the employability of the mentally impaired according to Early Irish legal commentary' (5th Annual Workshop on Disease, Disability and Medicine in Medieval Europe, University of Nottingham, 3-4 December)

*Eoin O'Flynn*:
- 'The organisation of kingship in Mide c. 600-900' (International Medieval Congress, Leeds, England, July)

*Elliott Lash:*
- 'The re-analysis of pre-Old Irish to Old Irish copular clauses" (International Congress of Historical Linguistics, National Museum of Ethnology, Japan, July; Irish network of formal linguistics second workshop, Dublin City University, September)
- "Degrammaticalization and Irish 'ro'" (Celtic linguistics symposium, Edinburgh, December)

*Helen Imhoff*:
'Art and Treóit in *Fástini Airt meic Cuind*' (XIV International Conference of Celtic Studies, NUI Maynooth, August)

**1.12 Cúrsaí in ollscoileanna Éireannacha / Courses in Irish universities**
Michelle O Riordan: Irish Literature module (1st Year Bachelor in Arts and Theology, Mater Dei Institute of Education, Dublin City University (September to April).

**1.13 Scrúdaitheoireacht Sheachtrach, etc./External Examining etc.**
Fergus Kelly: External examiner, Department of Early and Medieval Irish, University College, Cork (2011-12). Malachy McKenna: Examiner for M.A. thesis, 'Notes on the Breton of the Canton of Brieg' (Pierre Noyer, University of Sydney, Australia). Michelle O Riordan: External examiner for first year BARSI students in DCU (Mater Dei Institute) and for MA Irish Studies in NUI, Galway. Aoibheann Nic Dhonnchadha: External examiner MA Thesis, Department of Languages, Tourism and Hospitality, Waterford Institute of Technology.

**1.14 Na Meáin Chumarsáide agus Aithne Phoiblí / Media and Public Awareness**

**Suíomh lín / Website of the School of Celtic Studies**
New content was added to the School of Celtic Studies website (www.celt.dias.ie) on a continuing basis under the direction of Pádraig Ó Macháin and Andrew McCarthy. Queries from outside scholars, students and the general public were dealt with.

**1.18 Coistí náisiúnta agus idirnáisiúnta /National and international committees**
Pádraig A. Breatnach: Elected to Council, RIA; Comité International de Paléographie Latine; member of Coiste Léann na Gaeilge (RIA). Aoibheann Nic Dhonnchadha: member of Fochoiste na bhFoilseachán (Coiste Léann na Gaeilge, RIA). Margaret Kelly: Secretary of Academic and Special Libraries section, Library Association of Ireland.

**1.17 Cuairteoirí agus Comhaltaí/Visitors and Associates**

*Ollúna cuarta / Visiting Professors*
Professor Robin Chapman Stacey (University of Washington, USA)
Prof. James McCloskey, (University of California, USA)
Professor Markku Filppula (University of Eastern Finland, Finland)

Professor Tomás Ó Cathasaigh (Harvard University)
Professor Pádraig P. Ó Néill (The University of North Carolina at Chapel Hill, USA)
Professor Melita Cataldi (University of Turin, Italy)
Professor Nancy Stenson (University of Minnesota, USA)
Professor Jan Erik Rekdal, (University of Oslo, Norway)

*Scoláirí cuarta / Visiting Scholars*
Overseas scholars (apart from those listed above under Visiting Professors) who availed of library and research facilities are included in the following list. In addition, the School accords library and research facilities to Irish-based scholars for consultation of materials lacking in the scholars' own institution and/or major libraries.

Brendan Kane (University of Connecticut, USA)
Anastasia Levchenko (Moscow State University)
Natasha Sumner (Harvard University, USA)
Eystein Dehl, (University of Bergen, Norway)
Sarah Connell (Northeastern University, Boston, USA)
Josephine Barton (University of Sydney)
Laura Aitken (University of Aberdeen)
Debbie Street (University of Technology, Sydney)
Joanna Shimmin (University of Cambridge)
Tamara Rechberger (University of Vienna)
Orit Eshel (Hebrew University, Israel)
Leah Klement (Princeton University, USA)
Jacqueline Borsje (University of Amsterdam, The Netherlands)
Veronica Phillips (University of Cambridge)
Peadar Ó Muircheartaigh (University of Edinburgh)
Aidan Breen (University of Massachusetts, Boston, USA)
Murray-Luke Peard (University of Sydney)
Margo Griffin-Wilson (Harvard University, USA)
Conn Mac Aogain (City University of New York)
Roy Flechner, (Trinity College Cambridge, England)
Tatyana Mikhailova, (Moscow State University, Russia)
Gordon Ó Riain (Uppsala University, Sweden)
Elizabeth Boyle (University of Cambridge, England)
Emanuela Sanfelici, (University of Pisa, Italy)
Miranda Hales (University of Glasgow)
Veronica Gufler (University of Vienna)
William Mattingly (Florida Gulf Coast University, USA)
Aoife O Farrell (University of British Columbia)
Jeremy De Angelo (University of Connecticut, USA)
Gretchen Kern (University of Cambridge, Mass., USA)
Gill Diamant (Hebrew University of Jerusalem, Israel)
Ksenia Kudenko (University of St. Petersburg, Russia)
Timothy Causbrook (University of Sydney)
Oxana Dereza (Moscow State University)
Georgia Lynn Henley, (University of Cambridge, UK)
Polina Morozova (Moscow State University)
Qiu Farvgzhe (Oxford University, UK)
Linda Brady (University of Connecticut, USA)
Ruth Egger (University of Vienna)
Rebecca Shercliff (St. John's College, Cambridge)

Sarah Waidler (University of Cambridge, UK)
Daibhidh Robinson (Glasgow University)

# 2011 Research Report
# School of Cosmic Physics: Geophysics Section

## Contents

# 1 General

## 1.1 Research highlights

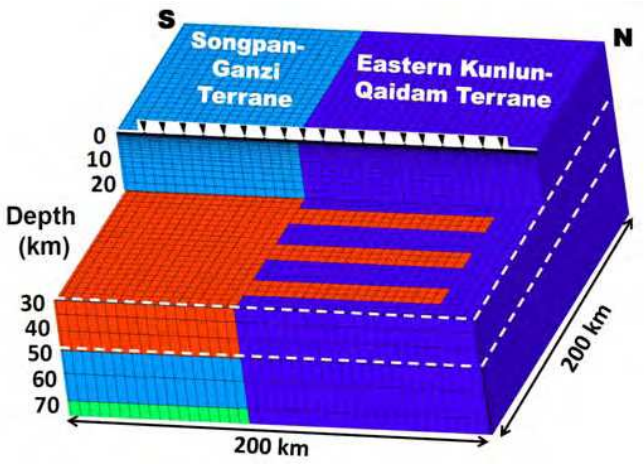
### 1.1.1 Continental deformation

In February, 2011, media in Ireland reported on the discovery of a previously unknown pattern of deformation of continental lithosphere, made by DIAS scientists, Assistant Professor Sergei Lebedev and Dr. Celine Tirel (Geophysics Section), and their co-workers in Germany. The team measured slight directional variations of seismic wave speeds in the Aegean region and determined directions of flow of the rock at depth. They found that the extension in the region is accompanied by viscous-fluid-like flow in the deep lithosphere, parallel to the direction of extension but at an angle to the major faults observed at the surface. The work is published in an article in the March issue of Nature Geoscience.

The research triggered a Science Foundation Ireland press release, was covered by the Irish Examiner and featured in Lebedev's interview on Science Spinning on Dublin City FM.

### 1.1.2 Penetrative melt progression

Mr. Florian Le Pape, Senior Professor Alan G. Jones, Dr. Jan Vozar, and Chinese colleagues submitted a paper to *Nature Geoscience* describing unequivocal evidence for electrical anisotropy observed at the northern edge of the Plateau that compromises the prior Kunlun Fault characterization as a significant rheological boundary4 between weak, warm Tibetan crust and the rigid Eastern Kunlun-Qaidam block. The authors suggest the anisotropic anomaly characterizes a hitherto unknown phenomenon of transgressive penetrative intrusion of melt from the Tibetan crust to the north, weakening the crust beneath the Kunlun Shan and accommodating the actual ongoing crustal shortening between India and the Qaidam basin.




The paper has been accepted for publication subject to minor revision.

### 1.1.3 IRETHERM initiated

The SFI-funded IRETHERM project was initiated in 2011 with the hiring of the four SFI-funded PhD students and two ENS-funded PhD students, and two SFI-funded post-doctoral fellows. A preliminary study was undertaken in the Dublin Basin with support from GT Energy.

## 1.2 New external funding received in 2011

### 1.2.1 SFI RFP proposal funded:

An SFI RFP2011 proposal by Martinec entitled "Combined glacial-isostatic adjustment and thermomechanical ice-sheet modelling to reconcile ice-mass variations inferred from sea-level and satellite observations (GIANICE)" was submitted in September 2010.A positive funding decision was received in March, 2011.
Daniel Bolte has started working on SFI Ph.D. project on January 10, 2012.

### 1.2.2 GOCE satellite data:

The ESA project proposal on the GOCE satellite data processing and interpretations, in which DIAS (Martinec) is one of six cooperating partners, has been approved for financing. The contract between ESA and the principal investigator (The University of Western Bohemia, UWB) was signed on October 20, 2011.
The complete sub-contract between the UWB and the DIAS was signed on December 22, 2011.
The time for undertaking the contract is 20 months and amounts to €38,963.

### 1.2.3 Short-Term Travel Fellowship:

Jones was successful with a Science Foundation Ireland Short Term Travel Fellowship proposal that will enable him to spend 5-6 weeks with Dr. Juan Carlos Afonso in Macquarie University, Sydney, Australia in October/November, 2012.

## 1.3 External funding requested in 2011

### 1.3.1 Marie-Curie Proposal

Dr. Jan Hagedoorn from GFZ Potsdam submitted the proposal for the Marie-Curie Fellowship at the DIAS on August 9, 2011. Prof. Martinec was supposed to act as the scientist in charge (at the the DIAS side).
**Title:** Combined downward continuation and spatio-spectral concentration techniques to reconcile the geomagnetic field at the core-mantle boundary inferred from satellite observations
**Duration:** 24 months
**Financial support:** €192,000
In the first evaluation, the proposal received 83 points (from 100) and passed the first threshold (70 points), but it has not been supported for financing in the second evaluation (cca 600 from 3200 proposals were recommended for financing).

### 1.3.2 SIRG Proposals

The Geophysics Section advertised internationally the opportunity for postdocs to submit SFI Starting Independent Researcher Grant (SIRG) proposals, for research on geothermal energy to be performed at DIAS. These highly competitive grants fund 4 years of salary of an experienced postdoc (PIs), the stipend of a Ph.D. student, hired and supervised by the postdoc, and research expenses, to a total of €400K. Three strong applicants have submitted SIRG proposals together with Assistant Professor Sergei Lebedev as their proposed mentor at DIAS: Drs. Nicola Piana Agostinetti (INGV, Italy), Abigail Jiménez Lloret (University of Almeria, Spain) and Celine Tirel (DIAS). The results will be announced in early 2012.

### 1.3.3 ERC Starting Grant Proposal

Lebedev submitted a European Research Council (ERC) Starting Grant proposal for the October 12, 2011, deadline, titled "*Geodynamic Tomography: Going beyond plate tectonics*".

# 2 Electromagnetic research activities

*Group Leader: Senior Professor Alan G. Jones*

## 2.1 Research Focus on Sustainable and Renewable Energy in Ireland

*M. Muller, A.G. Jones*

### 2.1.1 IRETHERM

**Background and research plan**

IRETHERM is an academic-government-industry collaborative project that started in April 2011, funded by a Science Foundation Ireland award (Grant No. 10/IN.1/I3022) to Principal Investigator Prof. Alan Jones at DIAS, which aims to develop a holistic understanding of Ireland's (all-island) low-enthalpy geothermal energy potential through integrated modeling of new and existing geophysical and geological data. Founding collaborators, who participated in the preparation of the research proposal, include Dr. Mark Muller (DIAS), Prof. Stephen Daly (UCD), Dr. Alistair Allen (UCC), Monica Lee and Taly Hunter Williams (GSI), Derek Reay (GSNI) and Roisin Goodman (SLR Consulting). Subsequent to the award of the SFI grant, several new collaborators have joined the project, who will provide additional knowledge, expertise and geological and geophysical data: Dr. Martin Feely (NUIG), Padraig Hanly (GT Energy) and Ric Pasquali (GeoServ Solutions).

IRETHERM's overarching research objective, over the 4½ year period of its funding, is to establish those geological settings and localities in Ireland with the greatest potential to provide significant volumes of hot geothermal waters or hot, dry rock. The project plans to:
(i) Develop multi-parameter modeling and interpretation software tools that advance state-of-the-art geophysical (electromagnetic, gravity, seismic) imaging of shallow and deep aquifers and granitic intrusions.
(ii) Understand both the 3D spatial variation in Ireland's radiogenic crustal heat-production and the origin of the local and regional heat-flow variations. New measurements of crustal heat-production in 3D (using mid- to lower-crustal xenoliths and borehole core) and of temperature and heat-flow variation will be modeled with existing constraints on the structure and thermal properties of the crust and lithosphere.
(iii) Test a strategic set of eight "type" geothermal targets with a systematic program of field electromagnetic surveys (MT, CSEM) (Figure 1), interpreted using our new modeling/inversion tools. Aquifer prospectivity will be based on high estimated porosity, subsurface continuity and depth, while granite (EGS) prospectivity will be based on large volume and depth extent and high radiogenic heat-production, in both cases in the presence of an elevated temperature gradient.

#### 2.1.1.1 Progress during 2011

Since project inception, the project has:
(i) successfully gathered together its complement of Ph.D. and postdoctoral researchers,

(ii) carried out two short surveys to test new CSEM equipment that will be critical in assessing shallow geothermal targets (Ireland's warm springs) and to assess the ambient noise levels and potential for acquiring MT data of adequate quality in a very important target area (the Dublin Basin),
(iii) supported, in an associated project, the M.Sc. research work of Markus Loewer investigating the geothermal energy potential of the Lough Neagh Basin in Northern Ireland and
(iv) initiated the modelling of Ireland's surface heat-flow data using the LitMod approach in order to understand the origin of subsurface temperature variation (see Petrophysical modeling section).

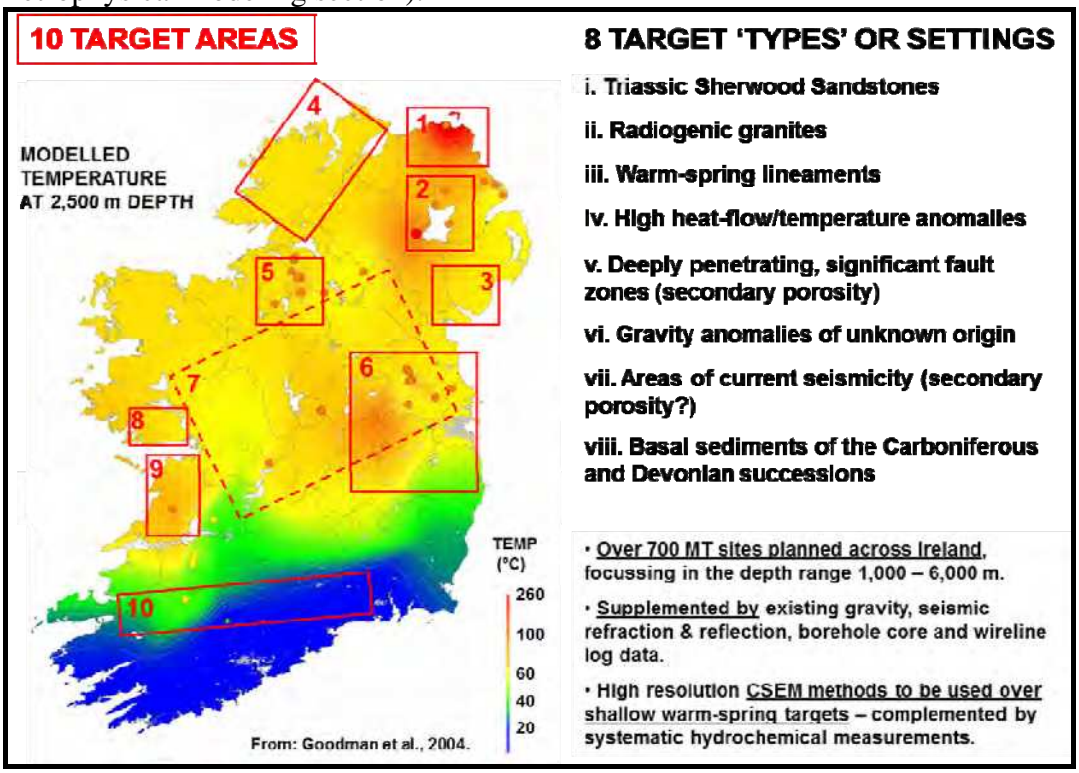



**Figure 1:** IRETHERM's planned survey areas (labelled 1 to 10) to assess eight different geological environments (as listed) for their geothermal energy potential. On the left, the target areas are overlain on a map of modelled crustal temperatures at 2,500 m depth (courtesy R. Goodman, SLR Consulting).

### *2.1.1.2 Research appointments and tasks*

All four SFI funded Ph.D. students have been appointed to the project and, with the exception of one student, started their research work at DIAS and UCD by September 2011:

**Sarah Blake** (based at DIAS). Research focus: Investigating Ireland's warm spring occurrences using electromagnetic and hydrochemistry methods.

**Thomas Farrell** (based at DIAS). Research focus: Geophysical investigation of Ireland's buried and exposed radiogenic granites, and expansion and modelling of Ireland's temperature and surface heat-flow database.

**Robert Delhaye** (based at DIAS – to start in January 2012). Research focus: Geophysical investigation of deep, hot aquifer targets hosted either in sedimentary rocks with high primary porosity (largely the Permo-Triassic successions in Northern Ireland) or in deeply penetrating shear zones characterized by high secondary porosity.

**Nicola Willmot Noller** (based at UCD). Research focus: Developing a 3-D model of Ireland's crustal radiogenic heat production through measurement of the radiogenic element compositions of rock samples from surface exposures, borehole core and preserved as xenoliths from the mid- to lower-crust.

Appointments have also been made to two UCD Earth and Natural Science (ENS) Programme Ph.D. studentships. Research carried out within the ENS framework will integrate seamlessly with the IRETHERM project.

**Chris Yeomans** (based at DIAS). Research focus: Geophysical investigation of the geothermal energy potential of the Greater Dublin area, present either in aquifers in sediments or shear zones in the Dublin Basin, or in the buried, radiogenic Kentstown and Drogheda granites.

**Tobias Frischle** (based at UCD). Research focus: Geochemical investigation of Ireland's exposed and buried radiogenic granites.

**Dr. Javier Fullea** was appointed to a Postdoctoral Research Fellowship (PDF) in May 2011, and will focus on modelling and understanding Ireland's surface heat-flow and subsurface temperature distribution using the petrologically and geophysically self-consistent LitMod approach. Dr. Fullea resigned from his PDF to take up a research position in Spain but will continue to work within IRETHERM until mid-2012.

Two competitions were run to identify a candidate to fill the remaining four-year PDF position. The successful candidate, **Dr. Jan Vozar**, has been appointed and will focus on developing multi-parameter, joint-inversion geophysical modelling and interpretation software tools. Dr. Vozar is due to take up the fellowship in May 2012.

#### *2.1.1.3 Pilot surveys*

Two pilot AMT/MT/CSEM field surveys were completed during Summer/Autumn 2011.

(i) 13-28 June, 2011. An AMT/MT profile was acquired across the margin of the Dublin Basin in the Newcastle/Rathcoole area, in the vicinity of GT Energy's very promising deep geothermal borehole (46 °C waters in a 1450 m deep borehole). The survey was carried out to assess the anticipated high ambient electrical and magnetic noise levels and the potential for acquiring MT data of adequate quality in a very important target area. While the recorded were found to be very noisy, initial models generated from shallower penetrating AMT data (produced by Ph.D. student Chris Yeomans) provide adequate depth of penetration for integration and reconciliation with a comprehensive geophysical and geological dataset that will be provided to the project by GT Energy. Deeper penetrating MT data that might provide information about the regional context of the prospect still require further processing aimed at dealing with the high noise levels prevalent in and around Dublin.

(ii) 2-7 October, 2011. A training/equipment testing CSEM survey was carried out in the vicinity of St Gorman's warm spring, near Enfield. Collaborator Dr. Thomas Kalscheuer and his Ph.D. student Joel Podgorski participated in the fieldwork within the framework of a collaborative agreement between DIAS and ETH Zurich in which instrumentation and knowledge will be shared to mutual benefit.

### *2.1.1.4 Geothermal energy potential of the Lough Neagh basin*

Research into the geothermal (hydrothermal) potential of the Sherwood Sandstone aquifer in Northern Ireland's Permo-Triassic Lough Neagh Basin was carried out by Markus Loewer during the period January – August 2011 as part of his IDEA League Joint Masters Program in Applied Geophysics (run by ETH, Aachen and Delft Universities). His work was jointly supervised by Muller and Jones at DIAS and Dr. Thomas Kalscheuer at ETH Zurich and resulted in successful graduation on 2 September 2011.

The investigation integrated 2-D magnetotelluric models with gravity and borehole log information and confirmed the lateral extent of the Sherwood aquifer across the basin in areas away from the borehole intersections (Figure 2). The maximum depth extent of the electrically conductive anomaly associated with the aquifer of about 2,300 m and a maximum predicted temperature of ~78 °C indicate a resource with high potential for exploitation for regional space-heating in an area designated in Northern Ireland as a growth node.

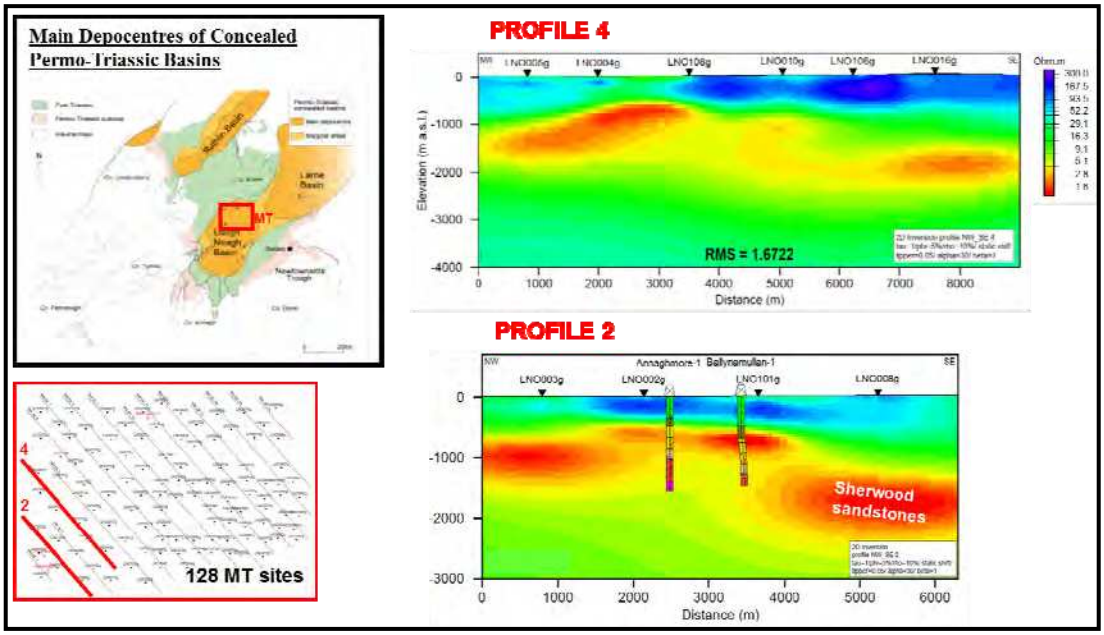



**Figure 2:** Locality plan of MT survey area in Northern Ireland over the Lough Neagh Basin and two representative 2-D MT smooth inversion models illustrating the high electrical conductivities (red anomalies) associated with the Sherwood Sandstone aquifer.

Research aimed at deriving the permeability and porosity characteristics of the Sherwood aquifer from the MT electrical conductivity models will continue both within IRETHERM and as part of the M.Sc. research project of student **Merijn de Block**, working at DIAS while registered at Utrecht University. His research, started in September 2011 and due for completion in July 2012, is supervised by Muller at DIAS, Dr. Colin Peach at Utrecht and Wouter van Leeuwen at IF Technology (Arnhem, Netherlands) and will examine the porosity and permeability of Irish sandstones in the Clare, Lough Neagh and Larne Basins using available MT and borehole wireline log data.

### *2.1.1.5 Wider impact of IRETHERM*

One notable aspect at this early stage of the project is the large amount of interest that the IRETHERM project has generated within the international geothermal energy research community. Several researchers, institutions and groups have approached us and we continue to pursue avenues for mutual collaboration.

(i) Profs. Jon Gluyas (Durham University, UK) and Paul Younger (Newcastle University, UK). The centre of geothermal energy research in the UK is shared between these two universities. Potential collaboration will provide the opportunity to learn from British experience of the geothermal potential of the Weerdale and Cornish granites and perhaps to participate in evaluating and monitoring their exploitation, as occurrences analogous to Irish granites.

(ii) Dr. Richard England (Leicester University, UK) who has a Masters student currently working on modelling and understanding heat-flow across the UK.

(iii) Dr. Beatrice Ledesert (Cergy-Pontoise University, France). The university has been heavily involved in research on the very influential Enhanced Geothermal System (EGS) project at Soultz-sous-Forets (the only currently operational pilot, low-enthalpy EGS electricity generating power-plant in the world).

(iv) Prof. Ruud Schotting and Ph.D. student Wouter van Leeuwen (Utrecht University) are seeking to explore for and assess shear zone hosted hydrothermal reservoirs in Carboniferous limestones in the Netherlands using magnetotelluric methods. Analogous Carboniferous limestones are present in Ireland, presenting scope for beneficial collaboration. DIAS has signed a collaborative agreement with Utrecht University.

(v) Prof. Michael Rhodes (University of Massachusetts, USA) who is seeking to investigate the potential of granites in Massachusetts and New England by adopting approaches similar to those to be used within IRETHERM.

(vi) Within a broader context, ongoing discussions with Dr. Guus Willemsen (IF Technology, Arnhem, Netherlands) may provide the opportunity for DIAS to expand its geothermal knowledge and experience into the area of high-enthalpy resources within the context of a proposed integrated assessment of a geothermal target in Uganda in which MT surveys will form a critical component.

*Thesis:*

**Loewer, M.** (2011), Investigation of the geothermal energy potential of the Lough Neagh Basin, Northern Ireland, using magnetotelluric and gravity modelling, M.Sc. degree awarded 2 September, 2011. Supervisor: **M.R. Muller**, co-supervisor: T. Kalscheuer, Swiss Federal Institute of Technology Zurich, Switzerland.

*Presentations:*

**Jones**, **A.G., M.R. Muller**, J.S. Daly, A. Allen, R. Goodman, N.H. Hunter Williams, M. Lee, and D. Reay (2011), IRETHERM: A New Project to Develop a Strategic and Holistic Understanding of Ireland's Geothermal Energy Potential, IGRM, NUIG, Galway, Ireland, 20-21 February.

**Jones**, **A.G., M.R. Muller**, J.S. Daly, A. Allen, R. Goodman, N.H. Hunter Williams, M. Lee, and D. Reay (2011), IRETHERM: A New Project to Develop a Strategic and Holistic Understanding of Ireland's Geothermal Energy Potential, EGU Meeting, Vienna, Austria, 4-8 April.

**Jones**, **A.G., M.R. Muller**, J.S. Daly, A. Allen, R. Goodman, N.H. Hunter Williams, M. Lee, D. Reay, M. Feely, P. Hanly, and R. Pasquali (2011), Harnessing Earth's heat for energy in Ireland: the IRETHERM project. **Invited** IGA Lectures, TCD, Dublin, 19 October and UCC, Cork, 20 October.

**Muller, M.R.**, **A.G. Jones**, J.S. Daly, A. Allen, R. Goodman, N.H. Hunter Williams, M. Lee, and D. Reay (2011), IRETHERM: A New Project to Develop a Strategic and Holistic Understanding of Ireland's Geothermal Energy Potential. GAI Biennial Geothermal Conference, Kilkenny, Ireland, 9-10 May.

**Muller, M.R.**, **A.G. Jones**, J.S. Daly, A. Allen, R. Goodman, N.H. Hunter Williams, M. Lee, D. Reay, M. Feely, P. Hanly, and R. Pasquali (2011), IRETHERM: Innovation within a new research project to explore and assess Ireland's deep, low-enthalpy geothermal energy potential, **Invited presentation**, Global Geothermal Energy Summit, Reykjavik, Iceland, 12-13 October.

### 2.1.2 Geothermal energy potential of the Mourne Mountain granites

The high radiogenic element (uranium, thorium and potassium) concentrations associated with the Mourne Mountain granites in Northern Ireland make this granitic intrusion one of the most prospective in Ireland for provision of Enhanced Geothermal System (EGS) energy. The major unknown parameters in terms of the potential for geothermal energy provision are the depth extent and volume of the intrusion. In a project logistically supported and funded by Geological Survey of Northern Ireland, DIAS conducted an MT survey across the Mourne Mountains during July-August 2010 to determine the subsurface geometry of the granites. Fifty-three AMT/MT sites, at roughly 1 km intervals, were recorded along three profiles across the Mournes.

Research on these data was carried out and completed by University of Birmingham M.Sci. students, Laura Ayres and Chris Yeomans, under the supervision of Muller at DIAS, co-supervised by Dr. Carl Stevenson at Birmingham. Both graduated in June 2011. The 2-D modelling of the MT data (Figure 3) focussed on establishing a better understanding both the geothermal energy potential of the Mournes granites and the mechanism of granitic melt emplacement into the crust. In the resistivity images of Figure 3, the Eastern Magmatic Centre is clearly less robust and has a reduced depth extent with respect to the Eastern Magmatic Centre, suggesting a lower geothermal energy potential. Both magmatic centres lack the benefits of thick, insulating sedimentary cover to enhance subsurface temperatures and predicted temperatures at 5,000 m depth based on the observed temperature gradient in the 600 m deep Silent Valley borehole (21 °C /km) are relatively modest – about 115 °C. Further MT data acquisition and investigation of the Mournes granites is planned during IRETHERM.

*Theses:*

**Ayres, L.A.** (2011), Constraints from magnetotellurics on the subsurface structure and emplacement of the Mourne Granites. M.Sc. degree awarded June, 2011. Supervisor: **M.R. Muller**, co-supervisor: C. Stevenson, University of Birmingham, UK.

**Yeomans, C.** (2011), Geothermal implications of the Mourne Mountains: constraints from magnetotelluric modeling. M.Sc. degree awarded June, 2011. Supervisor: **M.R. Muller**, co-supervisor: C. Stevenson, University of Birmingham, UK.

*Presentations:*

**Ayres, L.A., C. Yeomans**, C. Stevenson, **M.R. Muller**, D. Reay, and M. Desissa Ture (2011), Constraints from magnetotellurics on the subsurface structure and emplacement of the Mourne Granites, IGRM, NUIG, Galway, Ireland, 20-21 February.

**Yeomans, C., L. Ayres, M.R. Muller**, C. Stevenson, D. Reay, and M. Desissa Ture (2011), Geothermal energy potential of the Mourne Mountain granites: constraints from magnetotelluric modeling, IGRM, NUIG, Galway, Ireland, 20-21 February.

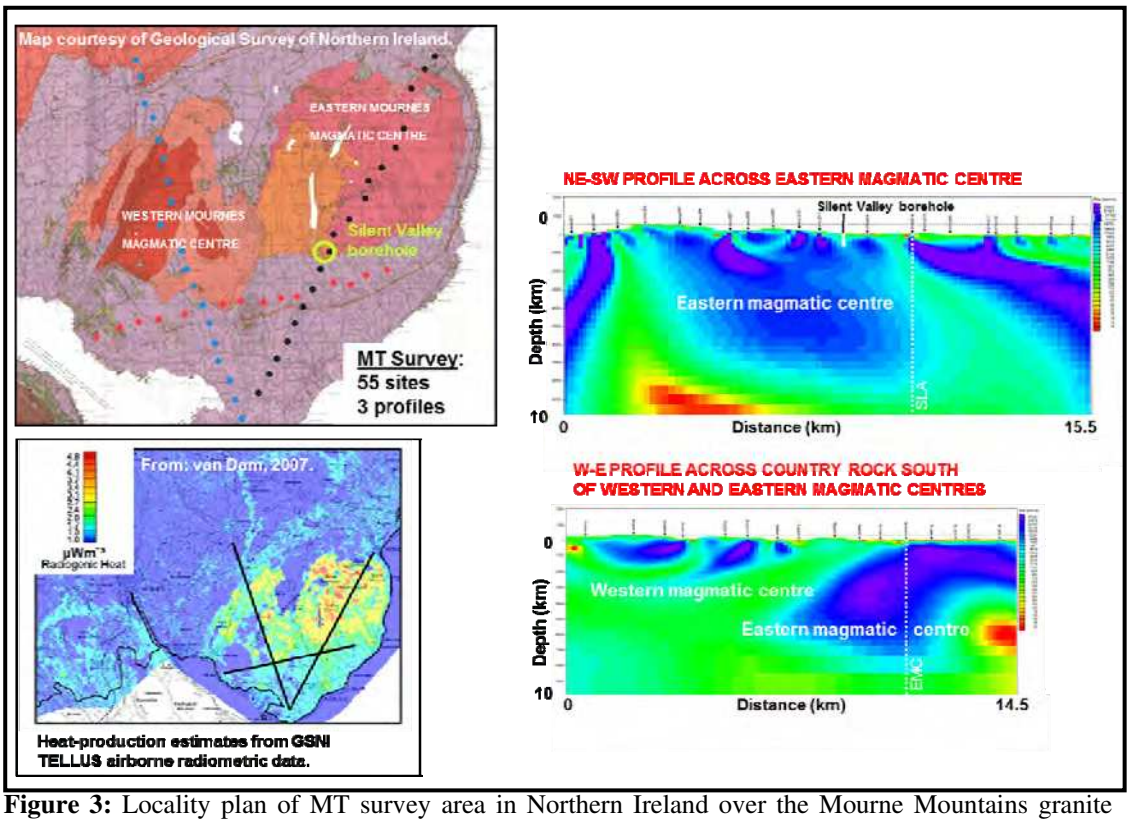



**Figure 3:** Locality plan of MT survey area in Northern Ireland over the Mourne Mountains granite complex and two representative 2-D MT smooth inversion models illustrating the high electrical resistivities (blue anomalies) associated with the granitic intrusions.

### 2.1.3 Carbon capture and sequestration (CCS) potential of the Clare Basin

Modelling of the Clare Basin data is in progress. Jones will submit a proposal to SFI's new Investigator Programme in 2012 for a grant to undertake further CCS work.

Spanish scientists have embarked upon aquifer characterization at the Hontomin CO2 Technical Development Plant as a prelude to CCS. CO2 will be injected into a dolomitized layer located at some 1450 m depth. A large number of experiments are in progress, and one component is electromagnetic (EM) mapping being conducted by the EM group of the University of Barcelona (Prof. J. Ledo and colleagues Profs. P. Queralt and A. Marcuello). Its scope is the development of EM methods for the characterization, modelling and monitoring of CO2 geological storage. Jones is a collaborator on this project; he is the official external supervisor of the Ph.D. student, Xènia Ogaya, and is giving expert advice to the project participants at all stages of the work.

Jones will profit from this research and will bring the discovered knowledge to bear to address identical problems in Ireland.

*Presentation:*

**Hogg, C.**, **M.R. Muller**, **A.G. Jones,** and P. O' Connor (2011), Assessing the regional structural geometry, variation of electrical resistivity and porosity estimates of the Ross Sandstone within the Clare Basin: preliminary results from a pilot magneto-telluric study, IGRM, NUIG Galway, Ireland, 20-21 February.

### 2.1.4 Compressed-air energy storage (CAES) potential of halite deposits in the Larne Basin

The Dublin-based wind-power company, Gaelectric, is investigating the possibility of dissolving suitable caverns for CAES in the Triassic and Permian halite deposits of the Larne Basin in Northern Ireland, within an 18 $km^2$ exploration area which they hold under license. Suitability of the halite deposits for CAES depends on the depth, thickness and lateral continuity of the halite layers – all of which are currently poorly known. DIAS, in a project funded by Gaelectric, has investigated the subsurface geological structure of the Larne Basin and its halite deposits using magnetotellurics. Sixty-seven AMT/MT sites, at roughly 500 m intervals, were acquired by DIAS within Gaelectric's exploration area during September 2010.

In work carried out by MSc student Sara Sihelnik during 2011, within the IDEA League Joint Masters program in Applied Geophysics, these data have been processed and modelled using 1-D and 2-D MT modelling approaches, supported by coincident gravity modelling. The work was jointly supervised by Muller and Jones at DIAS and Dr. Thomas Kalscheuer at ETH Zurich and resulted in successful graduation on 2 September 2011. Two reports were submitted to Gaelectric during 2011: (i) Report 3 (5 March, 2011) on the 1-D modelling of the MT site responses, and (ii) Report 4 (Final Report) (22 December, 2011) on the 2-D magnetotelluric and gravity modelling results.

The main conclusions emerging from the program of work carried out across the Larne Basin, with respect to defining the top and base of the target halite zone, are:

- The 2-D smooth inversion models reliably resolve the bases of both the basalt and the Mercia mudstone units on all profiles, and the depths of these boundaries are in good agreement with the depths observed in the 1-D models. Elevation changes of the top of the halite zone are therefore well determined across the survey area.
- The Sherwood sandstone conductor is less consistently resolved along the 2-D inversion profiles and is absent in several areas where it is resolved in the 1-D models. The base of the halite zone is therefore poorly defined by the 2-D inversions in some areas along the profiles. The 1-D models are found generally to have superior vertical resolution than the 2-D models and have resolved better the base of the halite zone. They are however less reliable in areas where strong lateral changes in resistivity are present.
- The joint gravity – MT modelling approach tested offers good potential for more reliably constraining the thickness and depth extent of the halite zone, particularly if it were to be coupled with a formal linking of the bulk density and the bulk resistivity of the halite zone through the halite-to-mudstone ratio. The joint modelling approach takes advantage of the fact that the halite zone is

characterised by both significantly higher electrical resistivities and lower densities than the overlying Mercia mudstones and underlying Sherwood sandstones.

- A thick, high-resistivity anomaly beneath one site was identified as a particularly interesting anomaly warranting further modelling work and investigation due to its potential association with a significantly thickened halite zone, with a higher percentage of halite to interbedded mudstone.

*Thesis:*

**Sihelnik, S.** (2011), Investigation of compressed air energy storage potential in the Larne Basin, Northern Ireland, using magnetotelluric and gravity methods. M.Sc. degree awarded 2 September, 2011. Supervisor: **M.R. Muller**, co-supervisor: T. Kalscheuer, Swiss Federal Institute of Technology Zurich, Switzerland.

*Reports:*

**Muller, M.R., A.G. Jones,** and **C. Hogg** (2011), 1-D Modelling of MT Site Responses (Report 3), Report submitted to Gaelectric, 5 March, 2011.

**Muller, M.R., A.G. Jones, S. Sihelnik,** and **C. Hogg** (2011), 2-D Magnetotelluric and Gravity Modelling (Final Report - Report 4), Report submitted to Gaelectric, 22 December, 2011.

### 2.1.5 Petrophysical modelling

Results from recent geophysical and mantle-xenolith geochemistry studies of the Kaapvaal Craton appear, at times, to provide disparate views of the physical, chemical and thermal structure of the lithosphere. Models from our recent magnetotelluric surveys across the Kaapvaal Craton indicate a resistive, 220–230 km thick lithosphere, for the central core of the craton. One recently published S-wave receiver function (SRF) study and several surface-wave studies suggest a thinner lithosphere characterised by an approximately 160 km thick high-velocity "lid" underlain by a low-velocity layer between 65–150 km thick. Other body-wave, surface-wave and SRF studies suggest that the (high-velocity) lithosphere is substantially thicker, in excess of 220 km. Mantle xenolith pressure-temperature arrays from Mesozoic kimberlites require the base of the "thermal" lithosphere (i.e., the depth above which a conductive geotherm is maintained) to be at least 220 km deep, to account for mantle geotherms in the range 35–38 $mWm^{-2}$. Richly diamondiferous kimberlites across the Kaapvaal Craton indicate a lithospheric thickness substantially greater than 160 km – the depth of the top of the diamond stability field.

In this ongoing research work we use the recently developed LitMod software code to derive, thermodynamically consistently, a range of seismic velocity, density and electrical resistivity models from layered geochemical models of the lithosphere based on mantle xenolith compositions. To help understand and resolve the apparent disparities described above, lithospheric models are found that simultaneously satisfy available geophysical observables: new surface-wave dispersion curves for the Kaapvaal Craton, magnetotelluric responses, surface elevation (assuming local isostasy) and surface heat-flow.

Results to date indicate that:
(i) A lithospheric thickness of 160 km is inconsistent with all geophysical (surface elevation, surface heat-flow and surface-wave dispersion curves) and petrological (depth of diamond stability field and palaeo-geotherms from P-T arrays) observables.

(ii) A lithospheric thickness of at least 220 km is required to satisfy the above constraints.
(iii) Lithospheric-mantle structures that consist of a single uniform chemical composition only (i.e., only harzburgite, high- or –low-temperature lherzolite) do not satisfy surface elevation constraints. A chemically layered structure is required (e.g., low-temperature lherzolite between 35–120 km depth, depleted harzburgite between 120–160 km and high-temperature lherzolite between 160 km and the base of the lithosphere at 220 km depth), consistent with chemical variation with depth observed in Kaapvaal mantle xenoliths.

*Publication:*

**Fullea, J.**, **M.R. Muller,** and **A.G. Jones** (2011), Electrical conductivity of continental lithospheric mantle from integrated geophysical and petrological modeling: Application to the Kaapvaal Craton and Rehoboth Terrane, southern Africa. *J. Geophys. Res. – Solid Earth, 116*, B10202, doi: 10.1029/2011JB008544.

*Presentations:*

**Muller, M.R.**, **J. Fullea,** and **A.G. Jones** (2011), Reconciling Electromagnetic, Seismic and Xenolith Constraints on Lithospheric Thickness and Composition of the Kaapvaal Craton, South Africa, EGU Meeting, Vienna, Austria, 4-8 April.

**Fullea, J.**, **M.R. Muller,** and **A.G. Jones** (2011), The Electrical Conductivity of the Continental Lithospheric Mantle: New Insights from Integrated Geophysical and Petrological Modelling, with application to the Kaapvaal Craton and Rehoboth Terrane, Southern Africa, ICCFD Meeting, Beijing, China, 25-29 April.

**Muller, M.R.**, **Fullea, J.**, and **A.G. Jones** (2011), Reconciling Seismic, Electromagnetic and Xenolith Constraints on Lithospheric Structure and Mesozoic modification of the Kaapvaal Craton, South Africa, ICCFD Meeting, Beijing, China, 25-29 April.

**Muller, M.R.**, **Fullea, J.**, and **A.G. Jones** (2011), Reconciling Electromagnetic, Seismic and Xenolith Constraints on Lithospheric Thickness and Composition of the Kaapvaal Craton, South Africa, GeoSynthesis Conference, Cape Town, South Africa, 28 August-2 September.

## 2.2 Southern African Magnetotelluric Experiment (SAMTEX)

*A.G. Jones, M. Muller, D. Khoza, M. Miensopust, P.-E. Share, and colleagues from WHOI*

### 2.2.1 Congo Craton

The work of David Khoza has focussed on understanding the geometry of cratonic lithosphere, particularly how intra-cratonic domain boundaries in Southern Africa influence tectonic evolution. Additionally this work focuses on providing new constraints on the lithosphere-asthenosphere boundary (LAB) geometry of the southern extent of the Congo craton and the Damara-Ghanzi-Chobe (DGC) orogen. Our results are derived from 2D and 3D inversion of MT data, acquired along semi-parallel profiles crossing the Kalahari craton across the DGC extending into the Congo craton. The crustal scale models (Figure 1) reveal that the DGC Central zone is high T/low P metamorphic zone, bounded on the north and south by zones of intermediate temperature and pressure metarmorphism, which define regions of structural thickening. A mid-lower crustal conductor is imaged along strike of the DGC. Regional metamorphism, fluid injections and/or structural movements are the

plausible mechanisms that could like give rise to a large scale crustal conductive feature like the one observed in the DGC. During periods of accretion and marked shortening and crustal thickening, graphite was preferentially emplacement along grain boundaries, and deep shear movement facilitated graphite inter-connectivity. The lithospheric anisotropic models (Figure 2(a-c)) suggest an elevated mantle conductivities in directions parallel to the profile (Ryy), particularly for the asthenosphere beneath the Congo craton at around 200 km depth. Possible causes of causes mantle anisotropy include (but not limited to) strain induced crystal preferred orientation (CPO) of anisotropic minerals, hydrogen diffusivity in mantle minerals and/or presence of partial melt.

Three-dimensional (3D) inversions (Figure 2(d))of the magnetotelluric (MT) data at 85 sites in northern Namibia map the LAB, and demonstrate cratonic signature associated with the southern extent of the greater Archean Congo craton with thick (>180 km) resistive lithosphere extending into northern Namibia. Furthermore, comparisons of the MT models with seismic tomography and geological outcrops suggest that Congo craton lithosphere extends significantly southwards beneath the DGC crust. The northern passive rift sequences appear to be over-thrusted onto the cratonic margin during the continental accretion *circa* 500 Ma. The younger DGC belt, which records the high-angle collision of Kalahari and Congo cratons during the amalgamation of Gondwana, has a relatively thin lithosphere (<160 km) and an upper crust which comprises resistive features related to the Pan-African magmatic intrusions. This result means that the current tectonic lines mapping the southern edge of the Congo craton needs to be revised and drawn further south.

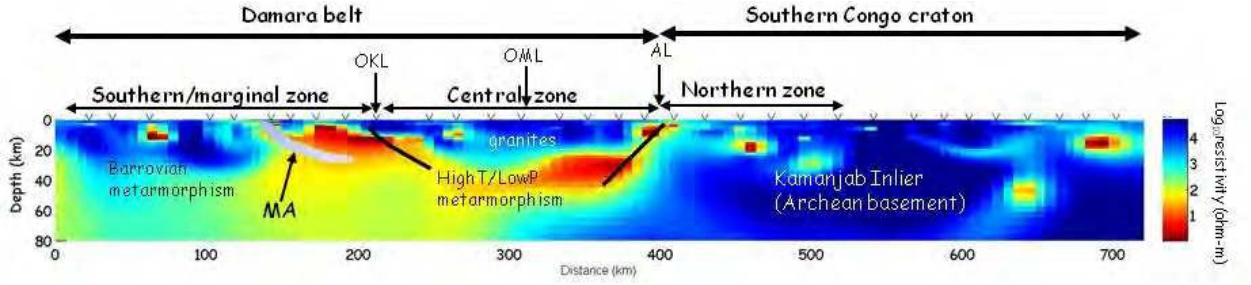



**Figure 1:** Crustal scale model of the ETO-KIM profile crossing the Archean Congo craton and Neoproterozoic Damara belt.

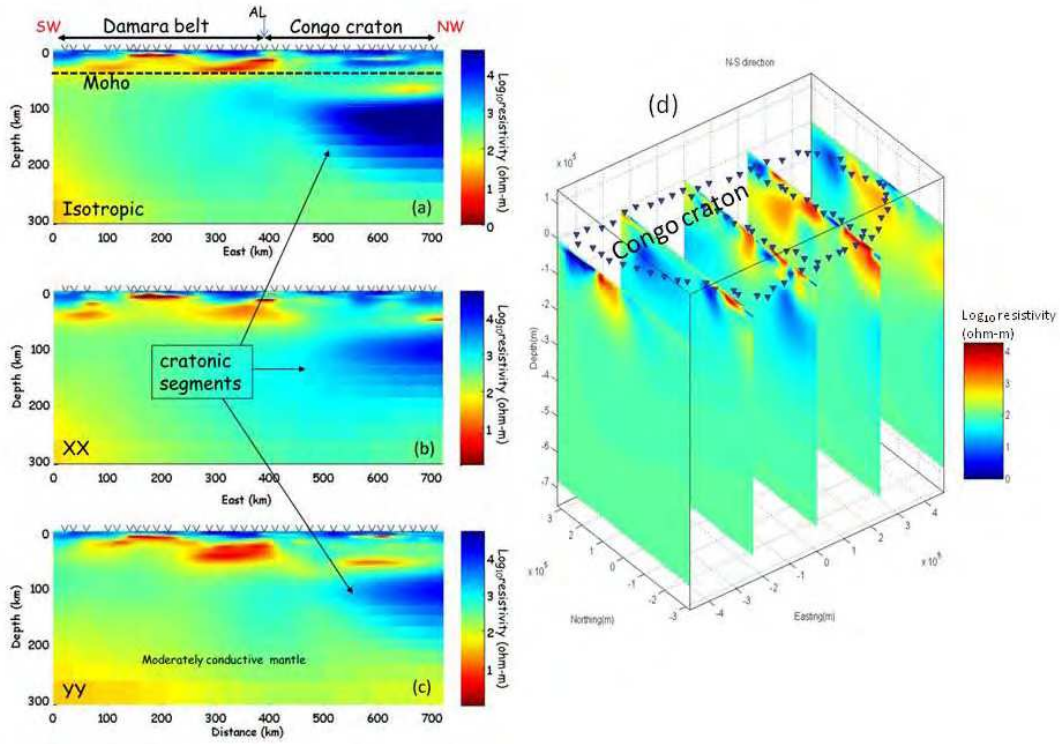



**Figure 2:** 2D Isotropic **(a)** and anisotropic **(b and c)** lithospheric models of the ETO-KIM profile showing conductivity structure in the direction perpendicular to the profile (Rxx) and parallel to the profile (Ryy).**(d)** Perspective view of 3D inversion model showing thick resistive lithosphere beneath the Congo craton.

*Presentations:*

**Khoza, D.T., A.G. Jones, M.R. Muller**, R.L. Evans, M.P. Hamilton, **M.P. Miensopust**, X. Garcia, P. Cole, T. Ngwisanyi, D. Hutchins, W. Pettit, H. Jelsma, T. Aravanis, C.J.S. Fourie, S. Webb, J. Wasborg, and The SAMTEX Team (2011), Electrical evidence of high angle convergence between Congo and Kalahari Cratons, Colloquium of African Geology, Johannesburg, 8-14 January.

**Khoza, D.T., A.G. Jones, M.R. Muller**, R.L. Evans, M.P. Hamilton, **M.P. Miensopust**, X. Garcia, P. Cole, T. Ngwisanyi, D. Hutchins, W. Pettit, H. Jelsma, T. Aravanis, C.J.S. Fourie, S. Webb, J. Wasborg, and The SAMTEX Team (2011), Lithospheric and thermal structure of the Southern Congo craton and Limpopo belt from magnetotelluric imaging, Geosynthesis, Cape Town, 28-1 September.

**Khoza, D.T., A.G. Jones, M.R. Muller**, R.L. Evans, M.P. Hamilton, **M.P. Miensopust**, X. Garcia, P. Cole, T. Ngwisanyi, D. Hutchins, W. Pettit, H. Jelsma, T. Aravanis, C.J.S. Fourie, S. Webb, J. Wasborg, and The SAMTEX Team (2011), Southern Africa Lithosphere: Quantitative comparison of Seismic and Electrical Parameters, Geosynthesis, Cape Town, 28-1 September.

**Khoza, D.T., A.G. Jones, M.R. Muller**, R.L. Evans, M.P. Hamilton, **M.P. Miensopust**, X. Garcia, P. Cole, T. Ngwisanyi, D. Hutchins, W. Pettit, H. Jelsma, T. Aravanis, C.J.S. Fourie, S. Webb, J. Wasborg, and The SAMTEX Team (2011), Southern Africa MagnetoTelluric Experiment (SAMTEX): Overview of observations and results, Geosynthesis, Cape Town, 28-1 September.

**Khoza, D., A.G. Jones, M.R. Muller**, S.J. Webb, and the SAMTEX MT Team (2011), The electrical lithosphere of Archean cratons: examples from Southern Africa, paper presented at AGU Fall Meeting, San Francisco, USA, 5-9 December.

**Jones, A.G., D.T. Khoza, M.R. Muller**, R.L. Evans, M.P. Hamilton, **M.P. Miensopust**, X. Garcia, P. Cole, T. Ngwisanyi, D. Hutchins, W. Pettit, H. Jelsma, T. Aravanis, C.J.S. Fourie, S. Webb, J. Wasborg, and The SAMTEX Team (2011), Lithospheric geometries revealed through electromagnetic imaging: SAMTEX (Southern Africa MagnetoTelluric Experiment) observations and results, **Invited**, AGU FallMeeting, San Francisco, California, USA, 5-9 December.

### 2.2.2 ZIM profile

*Publication:*

**Miensopust, M.P., A.G. Jones, M.R. Muller**, X. Garcia, and R.L. Evan (2011), Lithospheric structures and Precambrian terrane boundaries in northeastern Botswana revealed through magnetotelluric profiling as part of the Southern African Magnetotelluric Experiment (SAMTEX). *J. Geophys. Res. - Solid Earth*, *116*, B02401, doi:10.1029/2010JB007740.

### 2.2.3 DC powerline research

*Presentation:*

**Share, P.-E., A.G. Jones**, S. Webb (2011), Modelling of DC current flow between the Otjiwarongo and Katima Mulilo regions, Namibia, paper presented at GeoSynthesis 2011, Cape Town, South Africa, 28 August - 2 September.

### 2.2.4 Other

*Presentation:*

**Jones, A.G**., 2011. Combined seismological and electromagnetic studies of the lithosphere of Southern Africa. **Invited Keynote presentation**, The International Symposium on Deep Exploration into the Lithosphere, Beijing, China, 16-18 November.

## 2.3 PICASSO-TopoMed

*A.G. Jones, J. Fullea, J. Schmoldt, D. Kiyan*

### 2.3.1 PICASSO

***PICASSO: Programme to Investigate Convecting Alboran Sea System Overturn***

Mr. Jan Schmoldt successfully defended his thesis in October. Two papers are in progress from the work.

*Thesis:*

**Schmoldt, J.-P.** (2011), Multidimensional isotropic and anisotropic investigation of the Tajo Basin subsurface A novel anisotropic inversion approach for subsurface cases with oblique geoelectric strike directions. Ph.D. degree awarded November, 2011. Supervisor: **A.G. Jones**.

*Presentations:*

**Schmoldt, J.-P.** and **A.G. Jones** (2011), Using anisotropic approaches to realise 2D magnetotelluric inversion of a subsurface with depth-varying geoelectric strike direction - Synthetic model study and application to real data from the PICASSO Phase I project, EGU General Assembly, Vienna, Austria, 3-8 April.

**Schmoldt, J.-P., A.G. Jones, M. Muller, D. Kiyan, C. Hogg**, and O. Rosell (2011), Geometries and structures within the Iberian lithosphere and asthenosphere

beneath the Tajo Basin and Betic Cordillera revealed using magnetotellurics - Results of the PICASSO Phase I project, EGU General Assembly 2011, Vienna, Austria, 3-8 April.

**Schmoldt, J.-P., A.G. Jones, J. Fullea, M. Muller, C. Hogg**, and O. Rosell (2011), Magnetotelluric investigation of the lithosphere asthenosphere boundary beneath the Tajo Basin contrasted with results from seismic and thermal modelling studies - Results of the PICASSO Phase I project in the Iberian Peninsula, EGU General Assembly 2011, Vienna, Austria, 3-8 April.

### 2.3.2 TopoMed

***TopoMed: Plate re-organization in the western Mediterranean: Lithospheric causes and topographic consequences***

The overarching objective of the project is to define the geometries and determine the nature of the major crustal and upper mantle boundaries, through imaging electric structures that provide information on understanding the tectonic evolution of the Atlas Mountains of Morocco.

The magnetotelluric (MT) experiment across the Atlas Mountains region initiated in September, 2009 and ended in February, 2010. The experiment comprised acquisition of broad-band (crustal probing) and long period (mantle probing) MT data along two profiles: a N-S oriented profile crossing the Middle Atlas through the Central High Atlas to the east (profile MEK) and a NE-SW oriented profile crossing the western High Atlas towards the Anti Atlas in the west (profile MAR).

Our 2D MT inversion results (Ledo et al., 2011) from the MEK profile reveal a mid- to lower-crustal conductive layer stretching from the Middle Atlas southward towards the High Moulouya basin, and a low resistivity anomaly beneath the Anti Atlas at lower crustal scale. There is a gradual increase in mantle resistivity to the south which indicates a thickening lithosphere beneath the Anti Atlas.

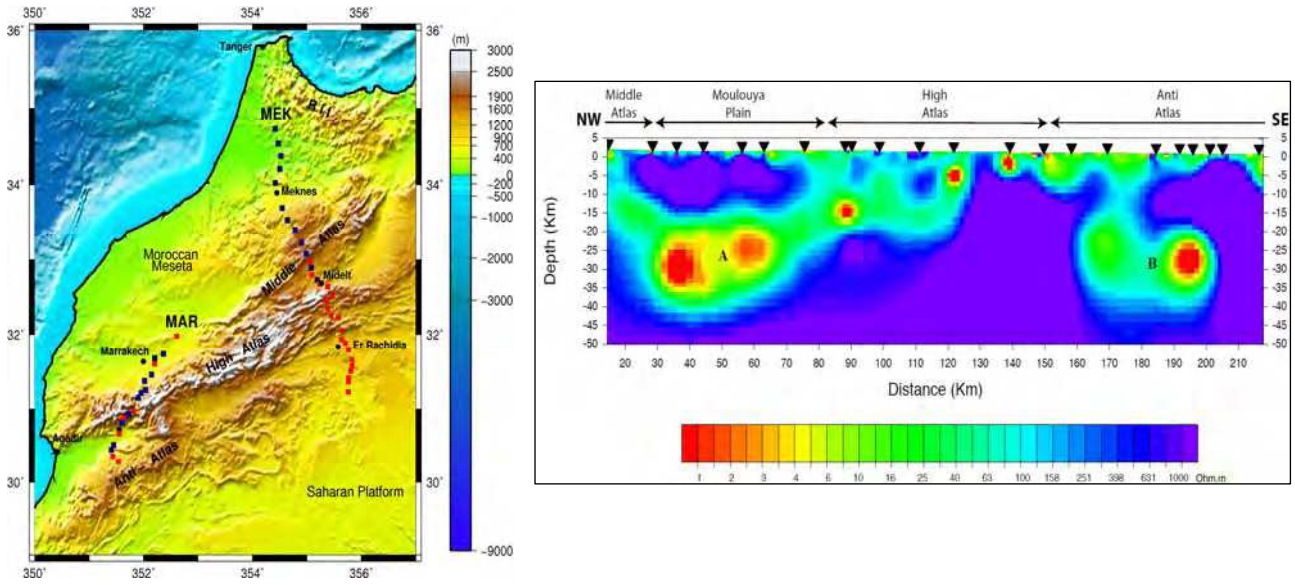



**Figure 1:** Topographic map of the study area showing the MT site locations across the Atlas Mountains. The red squares represent broad-band only sites and the blue ones represent both broadband and long period sites (on the left). Two-dimensional MT resistivity model obtained by inversion using both TE and TM mode resistivity and phases (on the right, from Ledo et al., 2011).

To validate the 2D inversion results, the MT data were inverted for 3D resistivity structure using both WSINV3DMT (Siripunvaraporn et al., 2005a) and ModEM (Egbert et al., 2011). In addition to inversion of the full impedance tensor, we ran the inversion with only off-diagonal components as input data. The main features deduced from the 2D interpretation are though also present in the models obtained by 3D inversions. The distinct conductivity difference between Middle-High Atlas and Anti Atlas correlates with the South Atlas Front fault, the depth extent of which appears to be limited to uppermost mantle (see Figure 2).

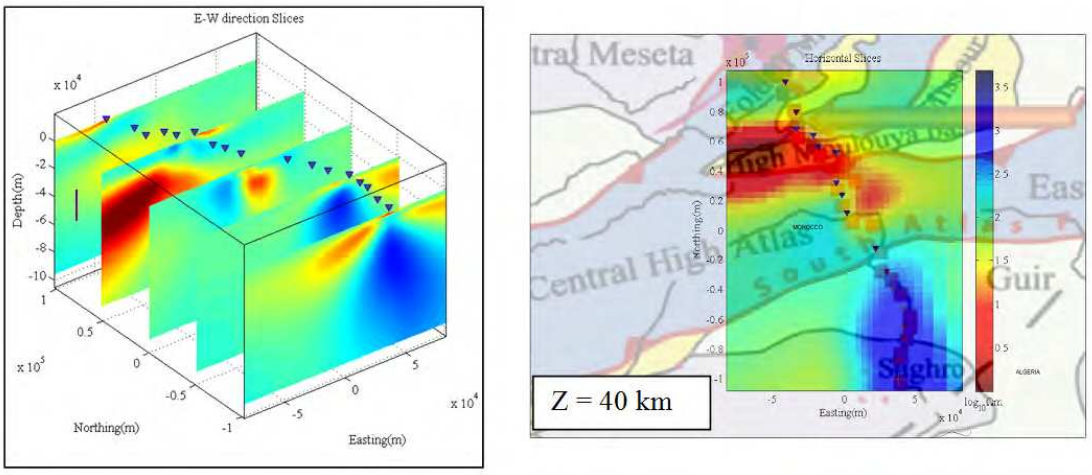



**Figure 2:** Model obtained from inversion of only off-diagonal components from MEK profile data.

*Publications:*

Ledo, J., **A.G. Jones**, A. Siniscalchi, J. Campanyà, **D. Kiyan**, G. Romano, M. Rouai, and TopoMed MT Team (2011), Electrical signature of modern and ancient tectonic processes in the crust of the Atlas mountains of Morocco, *Physics of the Earth and Planetary Interiors, 185*, 82-88, doi: 10.1016/j.pepi.2011.01.008.

**Jones, A.G., D. Kiyan**, and the TopoMed MT team (2011), Comment on "Deep resistivity cross section of the intraplate Atlas Mountains (NW Africa): New evidence of anomalous mantle and related Quaternary volcanism" by Anahnah et al. (2011), submitted to *Tectonics*.

*Presentations:*

**Kiyan, D., A.G. Jones, J. Fullea, C. Hogg,** J. Ledo, A. Siniscalchi, J. Campanyà, G. Romano, P. Moretti, M. Rouai, and the The TopoMed MT Team (2011), Lithospheric-scale geometry of the Atlas Mountains of Morocco revealed by magnetotelluric surveying, paper presented at EGU, Vienna, Austria, 3-8 April.

**Kiyan, D., A.G. Jones, J. Fullea**, J. Ledo, A. Siniscalchi, M. Rouai, J. Campanyà, G. Romano, P. Moretti, and the TopoMed Team (2011), Crustal and lithospheric imaging beneath the Atlas Mountains of Morocco, paper presented at TOPOMED Workshop, Institute of Earth Sciences Jaume Almera – CSIC Barcelona, Spain, 19–20 September.

**Kiyan, D., A.G. Jones, J. Fullea**, J. Ledo, A. Siniscalchi, M. Rouai, J. Campanyà, P. Moretti, G. Romano, and the PICASSO Phase II Team (2011), Geometry of the Atlas Mountains of Morocco revealed by electromagnetic imaging, paper presented at 7th Topo-Europe Workshop, Davos, Switzerland, 6-9 October.

Ledo, J., **A.G. Jones,** A. Sisnichalchi, J. Campanyà, **D. Kiyan**, G. Romano, M. Rouai and the TopoMed MT Team (2011), The TopoMed broad band magnetotelluric

experiment: crustal images of the Atlas Mountains of Morocco, paper presented at EGU, Vienna, Austria, 3-8 April.

## 2.4 INDEPTH

*A.G. Jones, J. Vozar, F. Le Pape, with colleagues from China University of Geosciences Beijing, the University of Alberta, Cornell University, Stanford University, and INDEPTH collaborators*

### 2.4.1 Central Tibet

The research of Vozar focused on 1D, 2D and 3D deep-probing electromagnetic studies of the Tibetan Plateau. In a frame of the SFI grant INDEPTH IV, the re-modelling of existing INDEPTH data was carried out, applying new inversion tools and new considerations such as anisotropy investigations and petro-physical modelling.

The studies presented on conferences and in the papers using magnetotelluric (MT) INDEPTH data describe the geometries of the geoelectrical crustal structures of the Banggong-Nujiang Suture, BengCo Jiali fault and ShuangHu Suture in central Tibet and Kunlun fault system in northern Tibet as well as thickness of lithosphere in INDEPTH region. The 2D modelling of line 500 confirms previous observations concluding that the region is characterized to first-order by a resistive upper crust and a conductive middle to lower crust that extends from the Lhasa Terrane to the Qiangtang Terrane with varying depth. The conductive layer is relatively uniform along whole profile, except for two breaks in the region of the Banggong-Nujiang Suture and 50 km south of it. Absence of attenuating high conductivity crustal layers in these short sections of line 500 coupled with careful selection of long period MT responses allow us to obtain information about deeper structures below the crust and reveal the possible existence of a high conductive layer localized at upper mantle depths. The same conductive structure setting is also present on the shorter 400 line. From deep electromagnetic sounding, supported by independent integrated petro-physical investigation, we can estimate the next upper-mantle conductive layer at depths from 200 km to 250 km below the Lhasa Terrane and less resistive Tibetan lithosphere below the Qiangtang Terrane with conductive upper-mantle in depths about 120 km. The 3D inversion models of all MT data from central Tibet show dominant 2D regional strike of mid and lower crustal structures equal N110E. This orientation is parallel to Shuanghu suture, BengCo Jiali strike-slip fault system and perpendicular to the India-Eurasia collision convergence direction. The lower crust conductor in central Lhasa Terrane can be interpreted more likely as 3D lower Indian crust structure, located to the east from line 500, than geoelectrical anisotropic crustal flow indicated by anisotropic 2D modelling of line 500. Similar studies have been performed on new and old MT data from Kunlun fault system.

Further deep investigations of the lithosphere-asthenosphere boundary (LAB) by integrated petrological-geophysical modelling of MT and seismic surface-wave data have been performed by the software package LitMod to proof previous electromagnetic investigation. The LitMod program facilitates definition of realistic temperature and pressure distributions within the upper mantle. This allows us define a bulk geoelectric and seismic model of the upper mantle based on laboratory and xenolith data for the most relevant mantle minerals, and to compute synthetic geophysical observables. The petro-physical models can be classified into two

different groups: i) the Lhasa Terrane and ii) the Qiangtang Terrane. Our results suggest an 80-120 km-thick, dry lithosphere in the central part of the Qiangtang Terrane. In the central Lhasa Terrane the LAB depth is about 200 km according to surface waves and topography. The presence of small amounts of water in the lithospheric mantle (<0.01 wt %) is required to fit the MT responses.

The results present new geometrical complexities and exhibit interesting features in crust and upper mantle missed on the initial interpretations to understand the nature of the Plateau and its evolution.

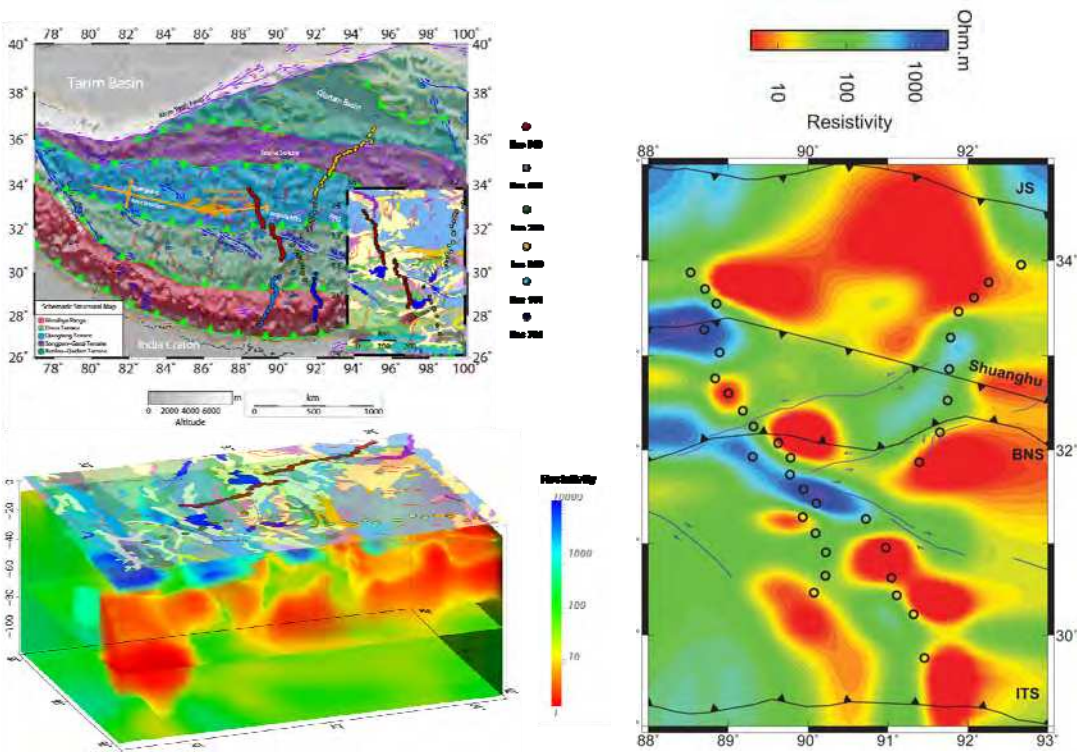



**Figure 1**: MT 3D final model visualisation with horizontal slice at 50km with surface strike-slips faults and sutures

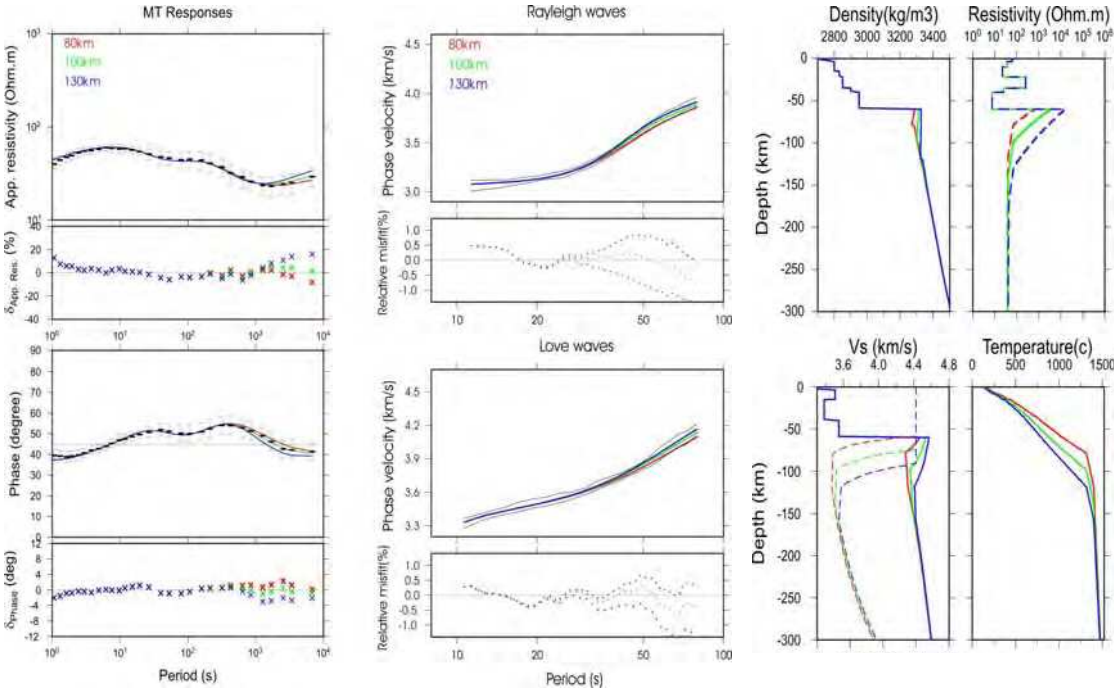



**Figure 2**: Dry lithosphere petro-physical modelling of Qiangtang Terrane. MT and seismic sounding curves and models for three different LAB in depths: —80 km, —100 km, —130 km.

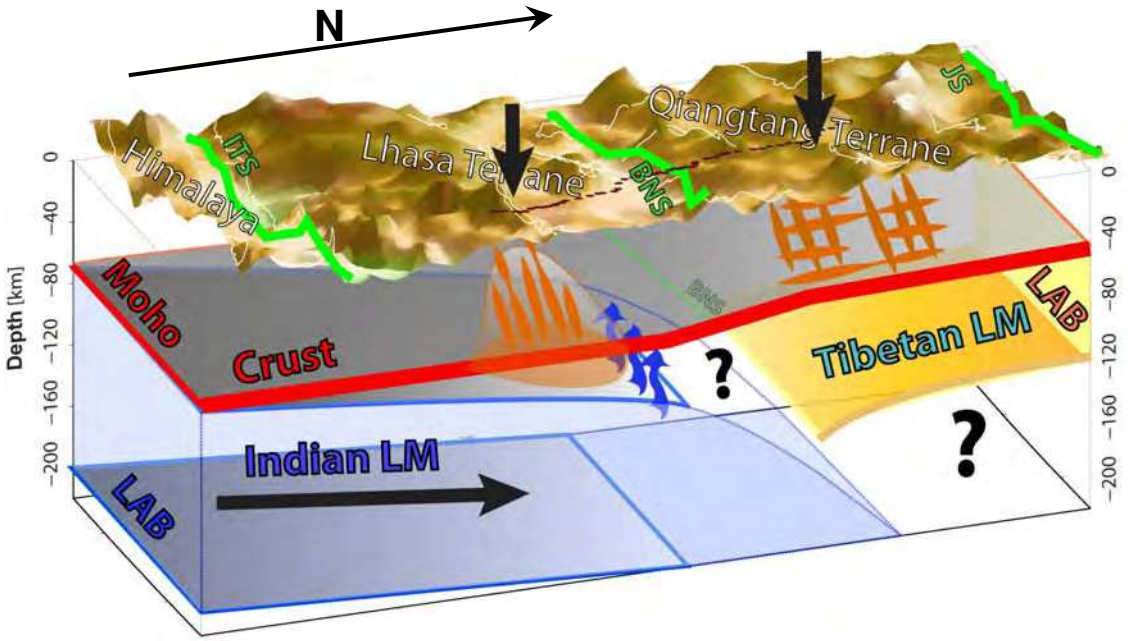



**Figure 3:** Final tectonic interpretation sketch for central Tibet

### 2.4.2 Northern margin

Determining the nature of the transition between weak Tibetan Plateau lithosphere and the surrounding rigid blocks is a key issue for understanding the ongoing India-Eurasia collision. The overall goal of Phase IV of the INDEPTH (International Deep Profiling of Tibet and Himalaya) project is to develop a better model of the structure

and evolution of the northern margins of the Tibetan Plateau. Between May and July 2010, long-period magnetotelluric (MT) data were acquired as part of INDEPTH Phase IV, including the new 6000 profile crossing the Kunlun Shan east of the 600 line, to complement broadband MT data already acquired in the area. In association with these new Phase IV MT surveys, existing MT 600 line data, collected during INDEPTH Phase III across the Kunlun Shan, were re-analyzed and re-modeled using more modern approaches. Both Phase III and IV profiles were investigated using 2D isotropic and anisotropic inversions, as well as 3D modeling.

The new evidence for electrical anisotropy observed in the 600 line resistivity model at the northern edge of the Plateau compromises the prior characterization of the Kunlun Fault as a significant rheological boundary between weak, warm Tibetan crust and the rigid Eastern Kunlun-Qaidam block. Moreover, south of the Kunlun fault, the middle to lower crustal conductive features of the new model of the 600 line data exhibit compelling spatial correlations with major regional tectonic features, implying structural control of crustal melt distribution – the presumed cause of the high conductivity – leading to localized decoupling of the deformation in time and space.

Preliminary 2D isotropic, anisotropic and 3D models of the INDEPTH Phase IV new 6000 profile confirm the presence of a conductive anomaly in the lower crust of the Kunlun Shan. The 2D anisotropic models highlight a preferred “along profile” orientation of this conductive feature, which agrees with the 600 line results.

The crustal anisotropic conductive anomaly observed in the Kunlun Shan may characterize transgressive penetrative intrusion of melt from the Tibetan crust to the north, weakening the crust beneath the Kunlun Shan and accommodating the actual ongoing crustal shortening between India and the Qaidam basin.

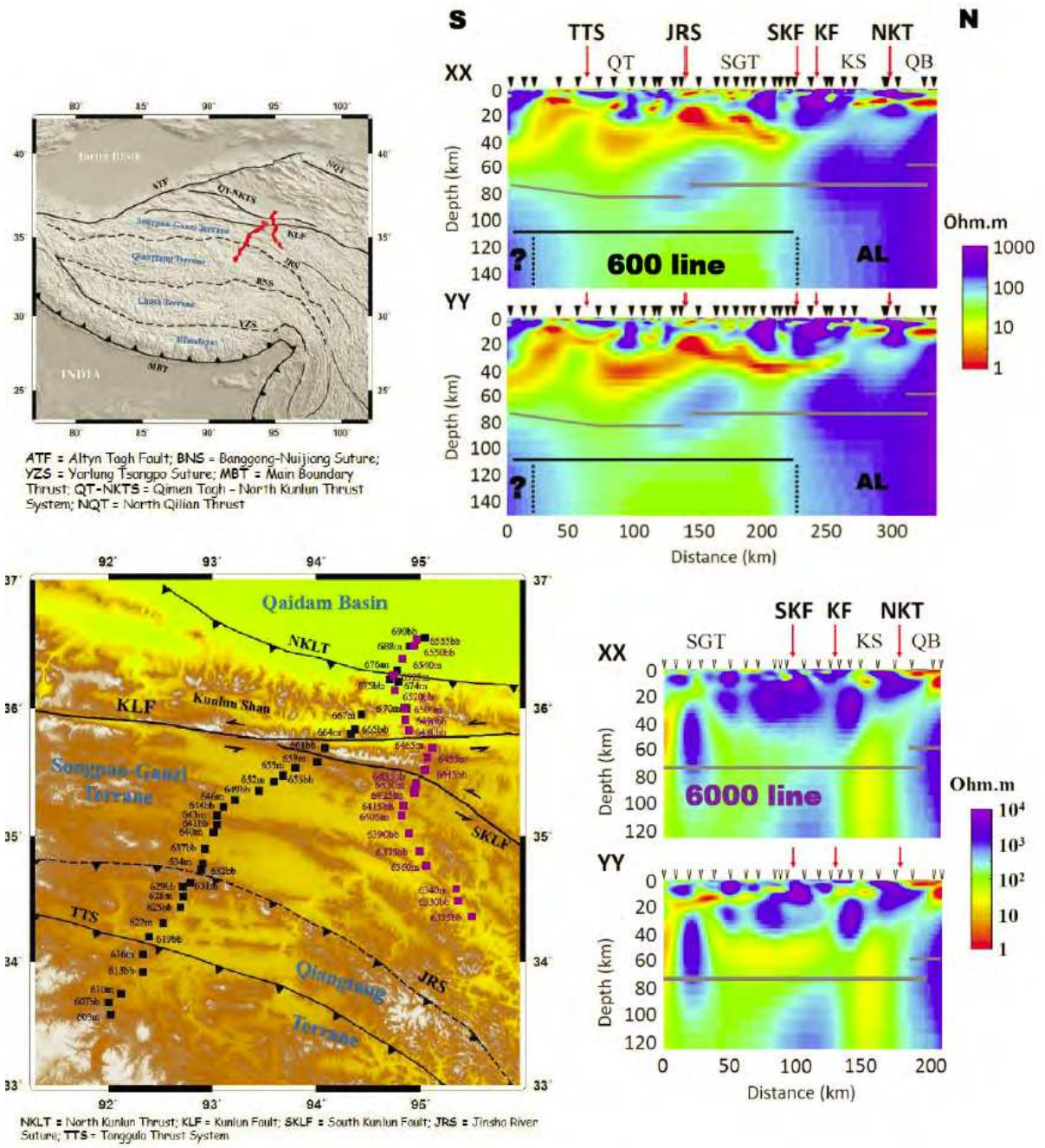



**Figure 4:** INDEPTH Phase III & Phase IV 2D anisotropic modelling. The Moho depth (Vergne et al., 2002; Karplus et al., 2011) is highlighted by the grey line. The black line shows the LAB location for a thin Tibetan lithosphere in the north part of the plateau imaged by seismic receiver functions (Zhao et al., 2011). AL – Asian Lithosphere, QT – Qiangtang Terrane, SGT – Songpan-Ganzi Terrane, KS – Kunlun Shan, QB – Qaidam Basin.

*Publications:*

**Le Pape, F., A.G. Jones, J. Vozar**, and W. Wei (2011), Crustal weakening and transgressive melt penetrative intrusion in northern Tibet, *Nature Geoscience*, accepted subject to minor revision.

**Vozar, J.**, **A.G. Jones, F. Le Pape,** and INDEPTH team (2011), Three-dimensional structures and geometries of central Tibetan Plateau from INDEPTH magnetotelluric data, paper prepared in 2011 and will be submitted to *Geophys. J. International* in 2012.

**Vozar, J.**, **J. Fullea, A.G. Jones, M. Aguis,** and **S. Lebedev** (2011), Electromagnetic, seismic and petro-physical investigations of the lithosphere–asthenosphere boundary in Central Tibet paper prepared in 2011 and will be submitted to *Geophys. J. International* in 2012.

*Presentations:*

**Jones, A.G**., **J. Vozar**, **F. Le Pape**, W. Wei, S. Jin, G. Ye, D. Hao, M.J. Unsworth, and the INDEPTH MT Team (2011), Constraints on Processes from the Electrical Conductivity of the Tibetan Plateau Lithosphere, **Invited** presentation, INDEPTH Workshop, Beijing, China, 15 November.

**Le Pape, F., A.G. Jones, J. Vozar,** W. Wei, and the INDEPTH MT Team (2011), Northern Tibet crustal and lithospheric mantle structures inferred from INDEPTH magnetotelluric data, paper presented at EGU General Assembly, Vienna, Austria, 3-8 April.

**Vozar, J.** (2011), Inversion results from secret model. MT 3D Inversion Workshop II, Dublin, Ireland, 30 March - 1 April.

**Vozar, J.** (2011), 3D MT inversion results from central Tibet. MT 3D Inversion Workshop II, Dublin, Ireland, 30 March - 1 April.

**Vozar, J.,** and **A.G. Jones** (2011), Multi-dimensional electromagnetic studies of lithospheric mantle and crust in the central Tibetan Plateau from INDEPTH magnetotelluric data, EGU General Assembly, Vienna, Austria, 3-8 April.

**Vozar, J.**, **A.G. Jones, F. Le Pape,** W. Wei, and INDEPTH team (2011), The lithospheric mantle and crust in the central Tibetan Plateau from INDEPTH electromagnetic data, EGU General Assembly, Vienna, Austria, 3–8 April.

**Vozar, J.**, **J. Fullea, A.G. Jones, M. Aguis,** and **S. Lebedev** (2011), Electromagnetic and petro-physical investigations of the lithosphere–asthenosphere boundary in Tibet and Central Europe, EGU General Assembly, Vienna, Austria, 3–8 April.

**Le Pape, F., A.G. Jones, J. Vozar**, W. Wei, H. Dong, M.J. Unsworth, S. Jin, G. Ye, J. Jing, L. Zhang, and C. Xie (2011), Crustal weakening and transgressive melt penetrative intrusion across the Kunlun Shan inferred from INDEPTH Phase III and Phase IV magnetotelluric data, AGU, San Francisco, USA, 5-9 December.

**Vozar, J.**, **J. Fullea, A.G. Jones, M. Aguis,** and **S. Lebedev** (2011), Electromagnetic, seismic and petro-physical investigations of the lithosphere–asthenosphere boundary in central Tibet, AGU Fall Meeting, San Francisco, USA, 5-9 December.

**Vozar, J.**, **A.G. Jones,** and **F. Le Pape** (2011), Three-dimensional structures and geometries of central Tibetan Plateau from INDEPTH magnetotelluric data, AGU Fall Meeting, San Francisco, USA, 5-9 December.

Zhang, L., W. Wei, M.J. Unsworth, M.J. Comeau, S. Jin, G. Ye, J. Jing, H. Dong, C. Xie, **F. Le Pape, A.G. Jones, J. Vozar**, and the INDEPTH MT Team (2011), Lithospheric structure across the Altyn-Tagh Fault on the north margin of the Tibetan Plateau revealed by magnetotelluric data, paper presented at AGU Fall Meeting, San Francisco, USA, 5-9 December.

## 2.5 Magnetotelluric theory

### 2.5.1 Electrical anisotropy

Collaboration with Montpellier on lithospheric anisotropy is continuing and Jones is planning to spend mid-May to mid-June 2012 as a guest of Professor Tommasi and her colleagues. As occurred during the prior two visits, a one week mini-workshop

will be held in Montpellier of those interested in electrical anisotropy (Jones, Mandolesi, DIAS; Moorkamp, Kiel now Leicester; Marti, UB; Roux, MI Barcelona).

*Publication:*

**Miensopust, M.P.**, and **A.G. Jones** (2011), Artifacts of isotropic inversion applied to anisotropic magnetotelluric data. *Geophys. J. International, 187*, 677 - 689, doi: 10.1111/j.1365-246X.2011.05157.x.

**Jones, A.G.** (2012), Distortion decomposition of the magnetotelluric impedance tensors from a one-dimensional anisotropic Earth. *Geophys. J. International*, in press, doi: 10.1111/j.1365-246X.2012.05362.x

*Presentation:*

**Miensopust, M.P.,** and **A.G. Jones** (2011), Artefacts of isotropic inversion applied to anisotropic magnetotelluric data, poster presented at EGU meeting, Vienna, Austria, 3-8 April.

### 2.5.2 Distortion effects

*Publication:*

**Jones, A.G**. (2011). Three-dimensional galvanic distortion of three-dimensional regional conductivity structures: Comments on "Three-dimensional joint inversion for magnetotelluric resistivity and static shift distributions in complex media" by Y. Sasaki and M.A. Meju (2006). *J. Geophys. Res*., **116**, B12104, doi: 10.1029/2011JB008665.

**Jones, A.G.** (2012), Distortion decomposition of the magnetotelluric impedance tensors from a one-dimensional anisotropic Earth. *Geophys. J. International*, in press, doi: 10.1111/j.1365-246X.2012.05362.x

## 2.6 Electromagnetic investigation of the Eyjafjallajökull

Due to the recent eruptive and highly disruptive volcanic events in 2010 in Iceland, scientific and societal interest is overwhelming in gaining as much information as possible about the volcanic structures and processes to enhance the understanding of the partially glacier-covered Eyjafjallajökull and Katla volcanic systems. Numerous petrological, geochemical and geophysical investigations of these systems have already been published. However, to date no electrical or electromagnetic data have been acquired on these two volcanoes to attempt to image the resistivity structure beneath and around them, although electromagnetic methods are far more sensitive to fluid distribution (in this case partial melt) than any other geophysical methods.

In July 2011, DIAS in close co-operation with the Icelandic Geosurvey ISOR undertook an electromagnetic pilot survey at Eyjafjallajökull. At 26 locations around the volcano magnetotelluric (MT) data was acquired using Phoenix broad-band MT equipment. Additionally at 25 of the MT sites also transient electromagnetic (TEM) data were recorded. The overall quality of the MT as well as the TEM data is really good. The MT data shows 1D behaviour for the first 2-3 decades of data and therefore, all MT sites were in a first attempt 1D inverted. The 1D models indicate 2 conductive layers – one in a few km depth, where possible a magma chamber could be located and one in 10-12km depth, which is consistent with earlier MT studies in Iceland showing such a layer of so far unknown source nearly everywhere beneath Iceland. The TEM data were used to correct for static shift effects present in the MT data. Especially sites close to strong topography show large static shift effects that

should be corrected for. Future tasks will be to analyse and model/invert the data beyond the 1D assumption and obtain a good justification to apply TEM and MT on a larger array for more detailed investigation.

*Presentations:*

**Miensopust, M.P., A.G. Jones**, Gylfi P. Hersir, and Arnar M. Vilhjálmsson (2011), Electromagnetic investigations of resistivity structures around and beneath the Eyjafjallajökull volcano, Southern Iceland: preliminary results, poster presented at Schmucker-Weidelt-Kolloquium, Neustadt an der Weinstrasse, Germany, 26-30 September.

## 2.7 Other electromagnetic research

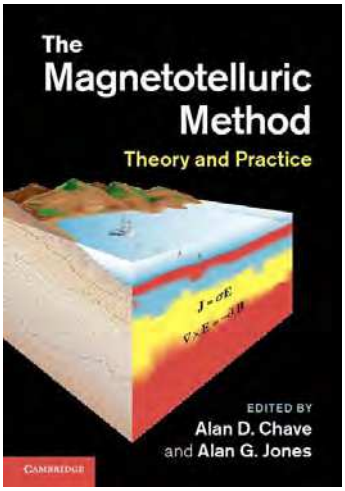
### 2.7.1 MaSca (Magnetotellurics in Scandes) - Jones

During the Summer of 2011 DIAS/Geo, led by Jones, took part in MaSca (Magnetotellurics in Scandes), a multi-institutional, multi-national research project investigating regional tectonic structures in northern Scandinavia. Twenty-two long-period, DIAS-owned LEMI instruments were contributed to the large pool used for mapping subsurface electrical conductivity. The geological structure of Lapland is a key area in understanding Archean and Proterozoic tectonic interactions, especially how Scandinavia formed when Greenland collided with the Baltic plate (shield). DIAS's MT technician, C. Hogg, deployed long period instruments across Sweden and Finland in June, 2011. The project's lead P.I., Dr. Maxim Smirnov is a frequent collaborator with DIAS/Geo, and we use his robust processing software. Currently the data from the MaSca project is being processed and modelled. DIAS Geophysics will maintain this excellent collaboration for any future phases of MaSca MT fieldwork.

### 2.7.2 CAMTEX/Insipient Rifting – Jones, Muller

The NSF Insipient Rifting (IR) project, led by WHOI (Dr. Rob Evans), Phase I MT fieldwork commenced in September 2011 in Botswana and concluded in early-November in SW Zambia. Data acquired using DIAS equipment will be modelled and interpreted by Khoza (densified OKA profile) and Miensopust (extrnsion of ZIM profile into Zambia).

CAMTEX – Central African MT Experiment – will take deep-probing reconnaissance MT technology, proven highly successful on SAMTEX, into central Africa (Zambia, Malawi). CAMTEX Phase I is planned to commence in April, 2012 (the gap due to the heavy rainy season in December to March), followed by IR-II in September-November 2012 and CAMTEX-II in April-June 2013 (funding permitting).




### 2.7.3 Other activities

#### 2.7.3.1 MT Book:

Jones, together with Dr. Alan Chave (Woods Hole Oceanographic Institution, completed editing the new book on magnetotellurics, The Magnetotelluric Method – Theory and Practice, that will be published by Cambridge University Press in April, 2012. The book is 550 pages in length, excluding the index, of which the largest chapter is the Distortion chaper (chapter 6), at almost 90 pages written solely by Jones.

The list of contents is:

1. Introduction to the magnetotelluric method: Alan D. Chave and **Alan G. Jones**
2. The theoretical basis for electromagnetic induction: Alan D. Chave and Peter Weidelt

3A. Earth's magnetic environment: 3A. Conductivity of Earth materials: Rob L. Evans
3B. Description of the magnetospheric/ionospheric sources: Ari Viljanen

4. The magnetotelluric response function: Peter Weidelt and Alan D. Chave
5. Estimation of the magnetotelluric response function: Alan D. Chave
6. Distortion of magnetotelluric data: its identification and removal: **Alan G. Jones**
7. The 2D and 3D forward problems: Chester Weiss
8. The inverse problem: William L. Rodi and Randall L. Mackie
9. Instrumentation and field procedures: Ian Ferguson
10. Case histories and geological applications: Ian Ferguson, **Alan G. Jones** and Alan D. Chave

#### *2.7.3.2 Presentations:*

Adetunji, A., I.J. Ferguson, and **A.G. Jones** (2011), The resistivity of the Grenville Province lithosphere as defined by magnetotelluric method, paper presented at CGU 2011, Banff, Alberta, Canada, 15-18 May.

Eaton, D.W.S., C. Hogan, J.C. Afonso, **A.G. Jones**, J. Tromp, M.S. Miller, and T.W. Becker (2011), SimLAB: Evaluation geophysical proxies for the Lithosphere-Asthenosphere Boundary, paper presented at AGU Fall Meeting, San Francisco, USA, 5-9 December.

Fishwick, S., **A.G. Jones**, and R.L. Evans (2011), A comparison of seismological and electromagnetic proxies for the LAB in southern Africa, paper presented at EGU 2011, Vienna, Austria, 4-8 April.

**Jones, A.G.** (2011), Mapping the electrical lithosphere-asthenosphere boundary (eLAB) and its correspondence with seismic (sLAB) and petrological (pLAB) LABs, Earthscope Workshop on the Lithosphere Asthenosphere Boundary, **Invited** presentation, 19-21 September, Portland, Oregon, USA.

**Jones, A.G**. (2011), Joint inversion of seismic and electromagnetic data for lithospheric parameters, **Invited** presentation, The International Symposium on Deep Exploration into the Lithosphere, Beijing, China, 16-18 November.

## 2.8 Main international collaborations

- U. Barcelona: Professors J. Ledo, P. Queralt, A. Marcuallo, A. Mari
- U. Bari: Professor A. Sinichalchi
- U. Leicester: Drs. S. Fishwick, M. Moorkamp, A. Avdeeva
- U. Montpellier, Profs. A. Tommasi, S. Demouchy
- U. Oulu: Prof. T. Korja, Dr. M. Smirnov
- China University of Geosciences Beijing: Profs. W. Wei, S. Jin, G. Ye
- Geological Survey of Canada: Mr. J. Craven, Dr. D. Snyder, Ms. J. Spratt
- WHOI: Drs. A.D. Chave, R.L. Evans
- Westfälische Wilhelms-Universität Münster, Germany: Dr. Michel Becken
- Memorial University, St Johns, Newfoundland: Professor Colin Farquharson
- Icelandic Geosurvey ISOR, Reykjavik, Iceland

# 3 Petro-physical modelling

*J. Fullea, A.G. Jones, M. Muller (Schrödinger Fellow)*

## 3.1 TOPO-MED

*J. Fullea, D. Kiyan, A.G. Jones*

Four MT sites along the MEK profile (MEK014 in the Middle Atlas, MEK022 and MEK025 in the High Atlas, and MEK030 in the Anti Atlas) were modelled using the software package LitMod. This software combines petrological and geophysical modelling of the lithosphere and sub-lithospheric upper mantle within an internally consistent thermodynamic-geophysical framework, where all relevant properties are functions of temperature, pressure and composition. In particular, LitMod is used in this work to define realistic 1D temperature, pressure, density and electrical conductivity distributions within the upper mantle, and to characterize the mineral assemblages given bulk chemical compositions. This allows us to determine the topography (local isostasy), surface heat flow, 1D geoid anomaly and magnetotelluric responses for different models of lithospheric composition and structure. Critically, we also assess the extent to which the uppermost lithospheric mantle might be partially molten. The lithosphere is relatively thin (70-90 km) in the Middle and High Atlas in agreement with the low seismic velocities imaged by seismic tomography and refraction studies, and the elevated SHF (50-80 mW/m2). The LAB deepens towards the SE in the Anti Atlas (140 km), where the simultaneous fit of the MT responses, Pn velocities, and measured SHF (<40 mW/m2) require a cold lithosphere. The elevated topography and the moderate decrease of the geoid anomaly with respect to the Middle Atlas (around 4 m) require a relatively depleted mantle composition in the Anti Atlas (i.e., Mg#= 91.8). The presence of a moderate amount of partial melt is required to reproduce the MT responses in sites MEK014, MEK025 and MEK030. The conductivity of the melt is determined as a function of temperature, pressure and composition on the basis of laboratory studies (Gaillard, 2004, Gaillard et al., 2008, Pommier at al., 2008 and Yoshino et al., 2010). The presence a partially molten layer in the lower crust-uppermost mantle N-S trending and potentially interconnected would produce strong anisotropic behaviour in the MT responses, i.e. phase splitting and/or off-quadrant impedance tensor diagonal elements , as seen in the data along the MEK profile.

## 3.2 SAMTEX

*J. Fullea, M. Muller, A.G. Jones*

The electrical conductivity of mantle minerals is highly sensitive to parameters that characterize the structure and state of the lithosphere and sub-lithospheric mantle and mapping its lateral and vertical variations gives insights into formation and deformation processes. We review state-of-art conductivity models based on laboratory studies for the most relevant upper mantle minerals and define a bulk conductivity model for the upper mantle which accounts for temperature, pressure and compositional variations. The bulk electrical conductivity model has been integrated into the software package LitMod, which allows for petrological and geophysical modelling of the lithosphere and sub-lithospheric upper mantle within an internally consistent thermodynamic-geophysical framework. We apply our methodology to model the upper mantle thermal structure and hydrous state of the western block of the Archean Kaapvaal Craton and the Proterozoic Rehoboth Terrane, in southern Africa, integrating different geophysical and petrological observables: namely

elevation, surface heat flow, magnetotelluric, and xenolith data. We find that to fit the measured magnetotelluric responses in both the Kaapvaal and Rehoboth terranes the uppermost depleted part of the lithosphere has to be wetter than the lowermost melt-metasomatized and refertilized lithospheric mantle. We estimate a present-day thermal lithosphere-asthenosphere boundary depth of 230-260 km and 150±20 km for the western block of the Kaapvaal and Rehoboth terranes respectively. For the Kaapvaal, the depth of the present-day thermal LAB differs significantly from the chemical LAB, as defined by the base of a depleted mantle, which might represent an upper level of melt percolation and accumulation within the lower lithosphere.

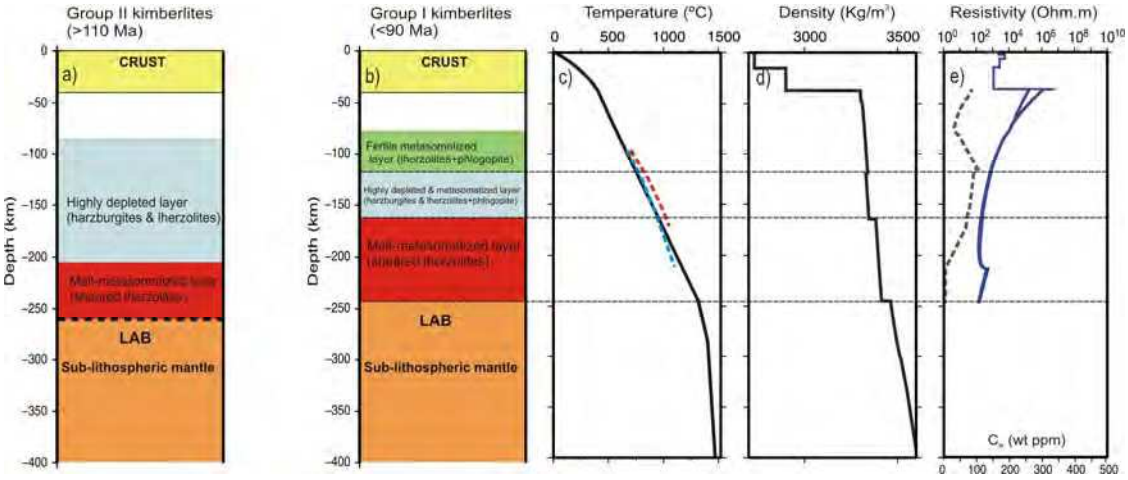



**Figure 1:** Lithospheric-mantle chemical structure in SW Kaapvaal derived from a) Group II kimberlites (>110 Ma), and b) Group I kimberlites (<90 Ma) (after Griffin et al., 2003). c) Black line is the calculated geotherm for our preferred model with a thermal LAB of 245 km; the red and blue dashed lines are the palaeo-geotherms for Group I and II kimberlites respectively. Paleo-geotherms are determined for peridotitic garnets assuming the Ni thermometer as described by Griffin et al. [2003]. d) Density profile for our preferred model with a thermal LAB of 245 km. e) Resistivity (blue solid lines, minimum and maximum HS bounds) and water content (grey dashed line) profiles for our preferred model.

## 3.3 IRETHERM

In the last decades geothermal energy is gaining specific weight in the context of renewable energies. In particular, recent technological developments are improving to make geothermal energy economically viable (e.g., water and space heating, and/or electricity generation) at relatively wide scales. Little is known of Ireland's geothermal resources, which could displace significant use of carbon-based fuels. IRETHERM is a four-and-a-half year, all-island, North-South, academic-government-industry collaborative project to develop a strategic and holistic understanding of Ireland's geothermal energy potential through integrated modelling of new and existing geophysical and geological data.

A marked regional increase in surface heat-flow is observed across Ireland, from ~40 mW/m2 in the south to >80 mW/m2 in the north. The origins of both the observed regional heat-flow trend and local temperature anomalies have not been investigated and are not understood. Although variations in the structure of the crust and lithosphere have been revealed by seismic experiments, their effects on surface heat-flow have not been modelled. Bulk variation in crustal heat-production across Ireland that may contribute significantly to the observed regional and local temperature variations has also not been determined.

We propose investigating the origins of both the observed regional heat-flow trend and regional and local temperature variations across Ireland, using the software package LitMod. This software combines petrological and geophysical modelling of the lithosphere and sub-lithospheric upper mantle within an internally consistent thermodynamic-geophysical framework, where all relevant properties are functions of temperature, pressure and composition. The major regional controls on both surface heat-flow and crustal temperatures are (a) crustal thickness and heat-production and (b) lithospheric thickness. These unknown variables are modelled in LitMod3D against known observations at surface – heat-flow, topography, gravity and geoid data – to identify a crustal and lithospheric mantle model that satisfies and accounts for all the observations at surface (most importantly in our context, heat-flow). The 3-D crustal and lithospheric models that emerge satisfying all observable constraints will, by accounting for the regional sources of heat in Ireland, allow us to isolate and examine in detail the extent to which local variations in both heat-production and thermal conductivity of subsurface lithologies might affect the distribution of temperatures in the depth range above 5 km.

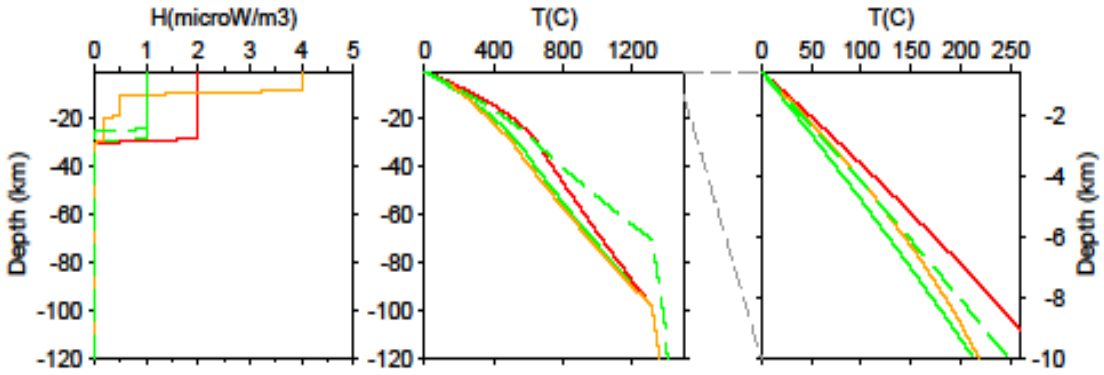



**Figure 1:** Modelling the trade-off between crustal and lithospheric thickness and the effect of crustal heat production.

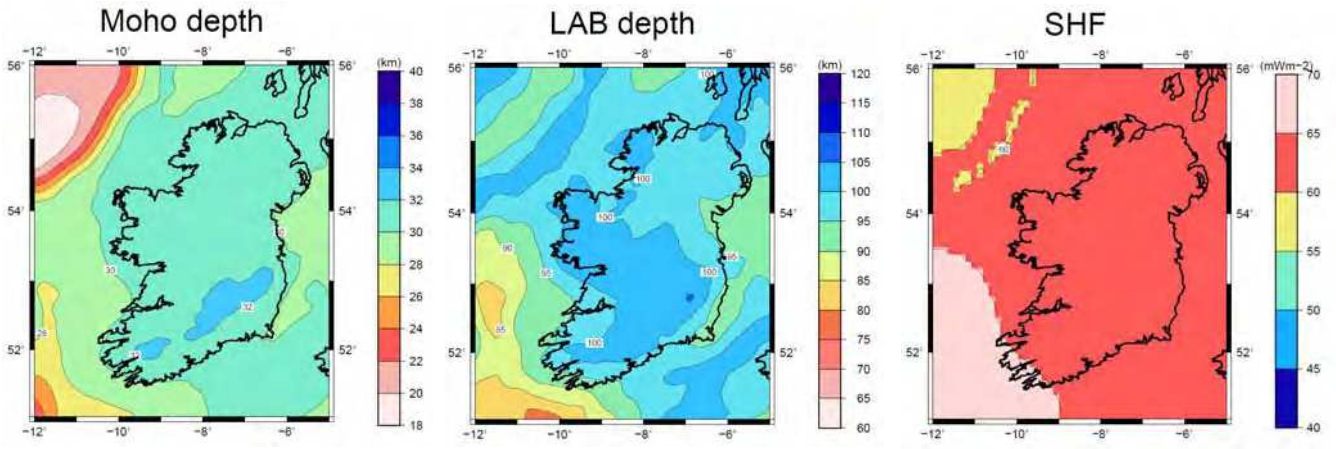



**Figure 2:** Crustal (left) and lithospheric (centre) model based on 1D inversion of topography and geoid anomalies filtered to retain the lithospheric signal (i.e., spherical harmonic degree and order >10). 3D computation of the surface heat flow (right) assuming constant thermal parameters in both the crust and the lithospheric mantle.

## 3.4 Other Activities

LITMOD4I: Joint inversion of geophysical and petrological data. Characterizing the lithospheric-sublithospheric upper mantle system: its composition, thermal state and dynamic evolution: (in collaboration with J.C. Afonso (GEMOC, Macquarie University, Sydney)).

In this project we specifically propose the development and implementation of a coupled geophysical-petrological inversion algorithm using a wide variety of data sets (surface and body waves, gravity, gravity gradients and geoid anomalies, surface heat flow, magnetotelluric, mantle and crustal xenoliths and elevation). A simultaneous fit of all these observables reduces the uncertainties associated with the modelling of each of them alone or in pairs. It will also allow us to distinguish, and have a better control on, thermal or compositional density variations at different depths, since these observables are differentially sensitive to shallow/deep, thermal/compositional density anomalies. This approach will help to overcome the massive time consumption required by purely trial and error (i.e. forward) models. Such high-resolution 3D models provide a reliable picture of the present day lithospheric structure which is a crucial constraint for geodynamic models (e.g., realistic mantle rheologies, snapshots of configurations of subducted lithosphere in regions of continental convergence). This study not only proposes a novel means to take geophysical modelling to the next level, but hopefully its outcomes will stimulate the technical innovations in geophysical research necessary to shed further light on the nature and evolution of the Earth's upper mantle.

Collaboration with other researchers from DIAS: S. Lebedev (joint inversion of Rayleigh and Love dispersion curves, elevation, surface heat flow and mantle composition in the India-Asia collision zone), J. Vozar (lithospheric modelling of MT, elevation, surface heat flow and mantle composition data in the Qiangtang and Lhasa Terranes, Tibet); and outside DIAS: Zuzana Tasarova from the Inst. of Geosciences, Vienna University of Technology, Austria (3D petrophysical-geophysical modelling of Western Carpathian-Pannonian Basin region using LitMod3D) and Sofie Gradmann and Jorg Ebbing from NGU, Trondheim, Norway (modelling the topography of the Scandes using LitMod3D).

*Publications:*

**Fullea, J., M.R. Muller**, and **A.G. Jones** (2011), Electrical conductivity of continental lithospheric mantle from integrated geophysical and petrological modelling: Application to the Kaapvaal Craton and Rehoboth Terrane, southern Africa, *J. Geophys. Res., 116*, B10202, doi: 10.1029/2011JB008544.

Jiménez-Munt, I., M. Fernàndez, J. Vergés, D. Garcia-Castellanos, **J. Fullea**, M. Pérez-Gussinyé, and J.C. Afonso (2011), Decoupled crust-mantle accommodation of Africa-Eurasia convergence in the NW-Moroccan margin, *J. Geophys. Res., 116*, B08403, doi: 10.1029/2010JB008105.

*Presentations:*

Afonso, J.C., **J. Fullea**, M. Fernández, J. Vergés, and H. Zeyen (2011), The lithosphere-sublithospheric upper mantle system beneath the Atlantic-Mediterranean Transition Region: advances and limitations from recent multidisciplinary approaches (solicited), EGU General Assembly, Vienna, Austria, 4-8 April.

Afonso, J.C., Y. Yang, **J. Fullea, S. Lebedev**, and S. Zlotnik (2011), A 3D multi-observable probabilistic inversion method for the compositional and thermal

structure of the lithosphere and sublithospheric upper mantle, EGU General Assembly, Vienna, Austria, 4-8 April.

Afonso, J.C., **J. Fullea**, Y. Yang, W.L. Griffin, **A.G. Jones**, J. Connolly, **S. Lebedev**, and S.Y. O'Reilly, 2011. 3D multi-observable probabilistic inversion for the compositional and thermal structure of the lithosphere and sublithospheric upper mantle. Contributed paper at: Fall AGU, San Francisco, 5-9 December.

Fernàndez, M., I. Jiménez-Munt, J. Vergés, D. Garcia-Castellanos, **J. Fullea**, M. Pérez-Gussinyé, and J.C. Afonso (2011), Decoupled crust-mantle accommodation of Africa-Eurasia convergence in the NW-Moroccan margin, EGU General Assembly, Vienna, Austria, 4-8 April.

**Fullea, J., M.R. Muller, A.G. Jones**, J.C. Afonso, and S. Zlotnik (2011), Imaging the lithosphere-asthenosphere boundary of southern Africa integrating elevation, surface heat flow, magnetotelluric and petrological data, EGU General Assembly, Vienna, Austria, 4-8 April.

Gradmann, S., J. Ebbing, and **J. Fullea** (2011), Tracing lithospheric mantle variations underneath Norway and Sweden - An integrated modelling approach with LitMod3D, EGU General Assembly, Vienna, Austria, 4-8 April.

**Kiyan, D., A.G. Jones, J. Fullea**, **C. Hogg**, J. Ledo, A. Siniscalchi, J. Campanyà, G. Romano, P. Moretti, M. Rouai, and the The TopoMed MT Team (2011), Lithospheric-scale geometry of the Atlas Mountains of Morocco revealed by magnetotelluric surveying, EGU General Assembly, Vienna, Austria, 4-8 April.

**Muller, M.R., J. Fullea**, and **A.G. Jones** (2011), Reconciling Electromagnetic, Seismic and Xenolith Constraints on Lithospheric Thickness and Composition of the Kaapvaal Craton, South Africa, EGU General Assembly, Vienna, Austria, 4-8 April.

**Schmoldt, J.-P., A.G. Jones, J. Fullea, M.R. Muller, C. Hogg**, and O. Rosell (2011), Novel Magnetotelluric investigation of the lithosphere-asthenosphere boundary beneath the Tajo Basin contrasted with results from seismic and thermal modelling studies - Results of the PICASSO Phase I project in the Iberian Peninsula, EGU General Assembly, Vienna, Austria, 4-8 April.

**Vozar, J., J. Fullea**, and **A.G. Jones** (2011), Electromagnetic and petro-physical investigations of the lithosphere–asthenosphere boundary in Tibet and Central Europe, EGU General Assembly, Vienna, Austria, 4-8 April.

**Muller, M.R., J. Fullea,** and **A.G. Jones** (2011), Reconciling Seismic, Electromagnetic and Xenolith Constraints on Lithospheric Structure and Mesozoic modification of the Kaapvaal Craton, South Africa, International Conference on Craton Formation and Destruction, Beijing, China, 25-29 April.

**Fullea, J.** (2011), Integrated geophysical-petrological modelling of surface-wave, topography, surface heat flow and xenoliths data: application to Central Mongolia's lithosphere, invited talk at 4th Workshop of TopoScandiaDeep, NGU, Trondheim, Norway, 31 May – 1 June.

**Muller, M.R., J. Fullea,** and **A.G. Jones** (2011), Reconciling seismic, electromagnetic and xenolith constraints on lithospheric structure and Mesozoic modification of the Kaapvaal Craton, South Africa, paper presented at GeoSynthesis, Cape Town, South Africa, 28 August - 2 September.

Afonso, J.C., **J. Fullea**, Y. Yang, W.L. Griffin, A.G. Jones, J. Connolly, S. Lebedev, and S.Y. O'Reilly (2011), 3D multi-observable probabilistic inversion for the compositional and thermal structure of the lithosphere and sublithospheric upper mantle, AGU Fall Meeting, San Francisco, USA, 5-9 December.

**Fullea, J., M.R. Muller,** and **A.G. Jones** (2011), Electrical conductivity of continental lithospheric mantle from an integrated geophysical and petrological approach: application to the Kaapvaal Craton, southern Africa, AGU Fall Meeting, San Francisco, USA, 5-9 December.

Gradmann, S., J. Ebbing, and **J. Fullea** (2011), A Boundary Zone in the Lithospheric Mantle beneath Norway and Sweden, AGU Fall Meeting, San Francisco, USA, 5-9 December.

**Vozar, J., J. Fullea, A.G. Jones, M. Agius,** and **S. Lebedev** (2011), Electromagnetic, seismic and petro-physical investigations of the lithosphere-asthenosphere boundary in central Tibet, AGU Fall Meeting, San Francisco, USA, 5-9 December.

# 4 Joint Inversion

*A.G. Jones, E. Mandolesi*

1D anisotropic inverse code have been developed and tested on both synthetic data and real data from Central Germany. Results from synthetic tests were presented at EGU (Mandolesi and Jones, 2011). Improvement of data fitting obtained using maximization of Mutual Information (MI) with a reference seismic model was presented at BGA conference (Mandolesi, 2011).

Inversion of data from the DIE station, in Central Germany, results in a model that agrees with updated models of the studied region. The joint probability distribution between high conductivity direction and fast seismic azimuth computed suggests common sources of electric and seismic azimuthal anisotropy. These results were presented during AGU Fall Meeting (Mandolesi and Jones, 2011)

Inversion of 2D anisotropic data is under development. Promising preliminary results were obtained using the classic Levenberg-Marquardt (LM) optimization algorithm in simple synthetic tests.

*Publication*

**Roux, E**., M. Moorkamp, **A.G. Jones**, M. Bischoff, B. Endrun, **S. Lebedev**, and T. Meier, 2011. Joint inversion of long-period magnetotelluric data and surface-wave dispersion curves for anisotropic structure: Application to data from Central Germany. Geophysical Research Letters, 38, L05304, doi: 10.1029/2010GL046358, pp 5.

*Presentations*

**Mandolesi, E.,** and **A.G. Jones** (2011), New constraints in magnetotelluric inversion, poster presented at EGU, Vienna, Austria, 4-8 April.

**Mandolesi, E.** (2011), Use of Mutual Information in Magnetotelluric Inversion, talk presented at BGA, Oxford, UK, 8-9 September.

**Mandolesi, E.,** and **A.G. Jones** (2011), Inversion of Magnetotelluric Data in Anisotropic Media Using Maximization of Mutual Information, poster presented at AGU Fall Meeting, San Francisco, USA, 5-9 December.

# 5 Geodynamic research activities

*Group Leader: Professor Zdenek Martinec*

Zdenek Martinec continued in glacial isostatic adjustment (GIA) modelling, the estimates of present-day mass balances in Antarctica and Greenland, interpreting

CHAMP magnetic data and preparing for interpreting SWARM magnetic data by modelling magnetic field induced by ocean circulations and by formulating the adjoint method for downward continuation of magnetic secular variations field from the Earth's surface down to the core-mantle boundary.

Modern modelling approaches to GIA are based on several techniques ranging from purely analytical formulations to fully numerical methods. Various European teams nowadays are independently working on the post-glacial rebound process in order to constrain the rheological profile of the mantle and the extent and chronology of the late-Pleistocene ice sheets which are prerequisites for the determination of the GIA contribution to geodetic observables. Martinec contributed to the benchmark study performed within the Working Group 4 of the ESF COST Action ES0701 “Improved constraints on models of Glacial Isostatic Adjustment”. The results of the benchmark have been published in Geophysical Journal International and it is the 8th most downloaded out of more than 400 GJI papers that were published in 2011, with more than 600 downloads."

In cooperation with Dr. Ondrej Soucek (Charles University in Prague) we revisited the results of the ISMIP-HEINO benchmark by first analyzing the differences in various model outputs using a wavelet-based spectral technique. Second, the ISMIP-HEINO benchmark experiments are recomputed with a novel numerical ice-sheet model based on the SIA-I algorithm that enables both the shallow-ice and a higher-order approximation of the ice-flow equations to be performed. To assess the significance of the higher-order approximation in the ISMIP-HEINO experiment, a numerical sensitivity study for the shallow-ice approximation (SIA) simulations is also carried out. A high sensitivity of the SIA model response to surface temperature perturbations is found. We conclude that the variations in ISMIP-HEINO results are due to the differences in (1) simulated basal temperatures and (2) numerical treatment of the basal sliding condition.

In cooperation with Dr. Ingo Sagen and Dr. Volker Klemann (GeoForschungsZentrum Potsdam) we performed a simultaneous inversion of gravity fields from the Gravity Recovery and Climate Experiment (GRACE) (August 2002 to August 2009) of four processing centres for glacial-isostatic adjustment (GIA) over North America and present-day ice-mass change in Alaska and Greenland. We applied a statistical filtering approach to reduce noise in the GRACE data by confining our investigations to GRACE coefficients containing a statistically significant linear trend. Selecting the subset of reliable coefficients (in the GRACE releases GFZ RL04, ITG 2010, JPL RL04 and CSR RL04) results in a non-isotropic smoothing of the GRACE gravity fields, which is effective in reducing the north-south oriented striping associated with correlated errors in GRACE coefficients. In a next step, forward models of GIA induced by the glacial history NAWI (Zweck & Huybrechts, 2005), as well as present-day ice mass changes in Greenland from ICESat (Sørensen et al., 2011) and Alaska from airborne laser altimetry (Arendt et al., 2002) are simultaneously adjusted in scale to minimize the misfit to the filtered GRACE trends. From the adjusted models, we derived the recent sea-level contributions for Greenland and Alaska (August 2002 to August 2009), and, interpreted the residual misfit over the GIA-dominated region around the Hudson Bay, Canada, in terms of mantle viscosities beneath North America.

In cooperation with dr. I. Rogozhina (GeoForschungsZentrum Potsdam), we analyzed the uncertainties in the models of the present-day Greenland Ice Sheet (GIS) that arise from ill-constrained geothermal heat flux (GHF) distribution in the Greenland region.

Within the context of dynamic GIS modeling, we considered the following questions: (i) What is the significance of the differences between the existing GHF models for the thermomechanical ice-sheet modeling studies dealing with the past evolution and present-day state of the GIS? (ii) How well do paleoclimatic simulations controlled by each of the three GHF maps agree with the today's knowledge of the GIS's thermal state and thickness? (iii) What portion of the misfit between the model and observations can be attributed to other source of uncertainties, namely the GIS history.

From the results of paleoclimatic simulations and sensitivity experiments, we concluded that differences in the GHF maps have a major effect on the history and present-day state of the GIS.

The ice-sheet model controlled by any of these GHF forcings reproduces the observed GIS state to only a limited degree and fails to reproduce either the topography or the low basal temperatures measured in southern Greenland. Sensitivity tests reveal that the misfit between the modeled and measured temperatures in central Greenland is a product of uncertainties in both the GHF and past climate forcing and cannot be amended by varying only the GHF forcing. The failure of the ice-sheet model in southern Greenland, however, originates to a large extent from the exaggerated GHF values suggested by all considered GHF maps.

In cooperation with Jan Dostal (GeoForschungsZentrum Potsdam), we were dealing with the magnetic field induced by ocean circulation. The study is motivated by the observations of the ocean-induced magnetic field by the CHAMP magnetic space mission. This type of magnetic field will be most likely observed by the SWARM magnetic mission (its launch has been postponed to July 2012). Such observations have the potential to be used as constraints on ocean dynamics. This has already initiated theoretical studies on the poloidal magnetic field induced by the horizontal ocean-circulation flow where the ocean layer is approximated by a single conductive sheet. Since the toroidal magnetic field cannot be modelled by this approximate model, we treat the ocean as a layer of finite thickness and model the toroidal magnetic field by a matrix-propagator technique with a source of electrical currents in the ocean layer. Although the primary toroidal magnetic field is not observable outside the oceans, it couples with a strong conductivity contrast between the oceans and continents and generates a secondary poloidal magnetic field which is observable by magnetic satellite missions and ground-based magnetic observatories situated close to the shoreline.

The paper on this subject was submitted to Geophysical Journal International for publishing in 2011. We obtained positive reviews on the manuscript appreciating a high level of mathematical considerations. On the other hand, the reviews asked for (i) a generalization of the background geomagnetic field such that not only a dipole term, but also higher-order multipole terms are considered, and (ii) an implementation of an ocean layer with a stratified electric conductivity due to variations in temperature and salinity. After extending the theory by the two generalizations and demonstrating their numerical influences, we submitted the revised version of the manuscript to Geophysical Journal International which has been accepted for publication in February 2012.

In 2011, Martinec has a new Ph.D. student at the Charles University in Prague, Faculty of Mathematics and Physics. His name is Libor Sachl, and the title of the Ph.D. project is 'Model of paleo-ocean circulation'. He started working on Ph.D. project in October 1., 2011, the duration is for 4 years.

Sajjad Sajjadi from the Limerick Institute of Technology has enrolled as a Ph.D. student at the Trinity College of Dublin in February 2012. Prof. Martinec will be a supervisor of his Ph.D. project. The application of Sajjad Sajjadi to be a student of DIAS has been approved by Prof. Tom Ray.

*Publications:*

Tanaka, Y., V. Klemann, **Z. Martinec**, and R.E.M. Riva (2011), Spectral-finite element approach to viscoelastic relaxation in a spherical compressible Earth: application to GIA modelling, *Geophys. J. Int., 184*, 220--234, doi: 10.1111/j.1365-246X.2010.04854.x.

Rogozhina, I., **Z. Martinec**, J.M. Hagedoorn, M. Thomas, and K. Fleming, (2011), On the long-term memory of the Greenland Ice Sheet, *J. Geophys. Res., 116*, F01011, doi: 10.1029/2010JF001787.

Spada, G., V.R., Barletta, V. Klemann, R.E.M. Riva, **Z. Martinec**, P. Gasperini, B. Lund, D. Wolf, L.L.A. Vermeersen, and M. King (2011), A benchmark study for glacial isostatic adjustment codes, *Geophys. J. Int., 185*, 106-132, doi: 10.1111/j.1365-246X.2011.04952.x.

Klemann, V., and **Z. Martinec** (2011), Contribution of glacial-isostatic adjustment to the geocenter motion, *Tectonophysics, 511*, 99-108, doi: 10.1016/j.tecto.2009.08.031.

Souček, O., **Z. Martinec**, and J. Velímský (2011), Vector potential formulation of a quasi-static EM induction problem: existence, uniqueness and stability of the weak solution, *Int. J. Geomath., 2*, 265-279, doi: 10.1007/s13137-011-0019-9.

Souček, O., and **Z. Martinec** (2011), ISMIP-HEINO experiment revised: effect of higher-order approximation and sensitivity study, *J. Glaciol., 57*, 1158-1170.

Dostal, J., **Z. Martinec**, and M. Thomas (2012), The modelling of toroidal magnetic field induced by tidal ocean circulation, *Geophys. J. Int.,* in press.

*Presentations:*

Souček, O., and **Z. Martinec** (2011), An attempt to simulate Heinrich's events, Meeting before REKLIM workshop, AWI Bremerhaven, Germany, 28 March.

Dostal, J., **Z. Martinec**, and M. Thomas (2011), Simulation of the ocean induced poloidal magnetic field variations by considering the conductivity contrast between ocean and continent, EGU General Assembly, Vienna, Austria, 3-8 April.

Horwath, M., I. Sasgen, B. Legrésy, F. Rémy, F. Blarel, J.-M. Lemoine, H. Dobslaw, **Z. Martinec**, and M. Thomas (2011), Antarctic ice mass balance from satellite geodesy: understanding the signal beyond linear trends, EGU General Assembly, Vienna, Austria, 3-8 April.

Klemann, V., J. Hagedoorn, and **Z. Martinec** (2011), Refinement of palaeotopography in modelling of glacial isostatic adjustment, poster presented at EGU General Assembly, Vienna, Austria, 3-8 April.

Rogozhina, I., O. Souček, **Z. Martinec**, J. Hagedoorn, K. Fleming, and M. Thomas (2011), Different present-day geothermal heat flux scenarios for the case of the Greenland Ice Sheet, poster presented at EGU General Assembly, Vienna, Austria, 3-8 April.

Sasgen, I., **Z. Martinec**, B. Wouters, M. van den Broeke, J. Bamber, and L. Sandberg-Sørensen (2011), Greenland ice-mass balance from satellite gravim-

etry: re-assessing the influence of glacial-isostatic adjustment, poster presented at EGU General Assembly, Vienna, Austria, 3-8 April.

Souček, O., **Z. Martinec**, and J. Velímský (2011), Quasi-static electromagnetic induction in spherical Earth: Vector potential formulation, poster presented at EGU General Assembly, Vienna, Austria, 3-8 April.

**Martinec, Z**. (2011), The adjoint sensitivity method of global electromagnetic induction for CHAMP magnetic data, Annual Meeting of the German Mathematical Society, Cologne, Germany, 18-23 September.

# 6 Seismology and geodynamics

*Group Leader: Assistant Professor Sergei Lebedev*

## 6.1 Ireland Array

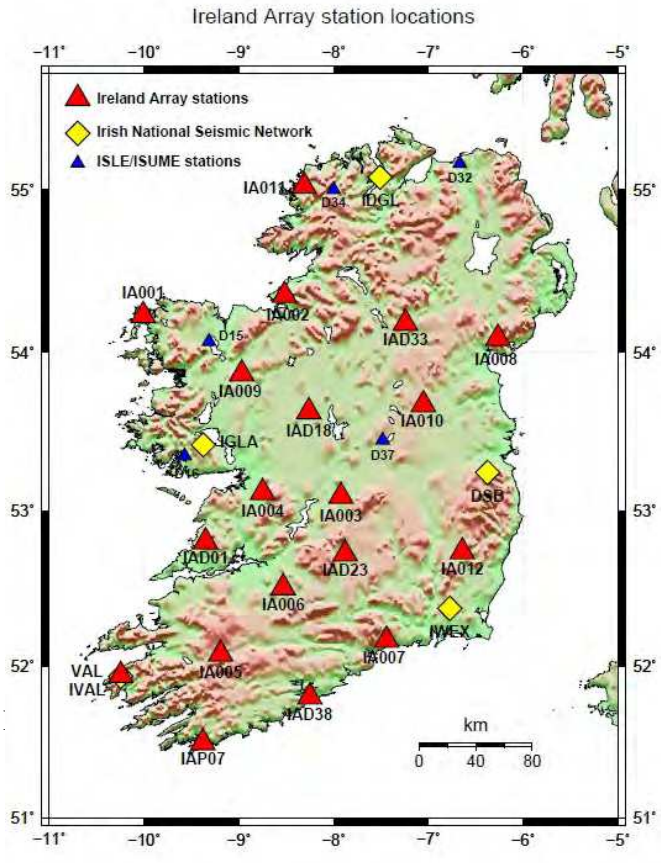
*S. Lebedev, P. Readman, A. Schaeffer, M. Agius, F. Hauser, J. Adam, B. O'Reilly, T. Blake, C. Horan, L. Collins*


Ireland Array is a major project that has been a collaboration of all seismologists in the Geophysics Section. The stations were installed in anticipation that this major new facility will help us attract new funding in the near future. (Three proposals have been submitted to the SFI SIRG programme in 2011 on research using Ireland Array data.)

The deployment of Ireland Array has been nearly completed in 2011, with 19 very-broad-band Trillium 120PA seismometers installed and recording and only one, 20th station still to be deployed.

Ireland Array website is now online at http://www.dias.ie/ireland_array, with information on the project, participants, instrumentation and example data and project outreach.

Ireland Array stations in the west of the country were deployed in time to record simultaneously with the broad-band instruments installed by Prof. Chris Bean and his group at UCD, installed in September-October along the western coast of Ireland.



Together, the deployments will make the west of Ireland one of the best instrumented locations in the world, for a period of a few months to a year. The data will be shared between DIAS and UCD. The combined coverage will enable seismic imaging of Ireland's crust and upper mantle with unprecedented resolution.

Rosse Solar-Terrestrial Observatory (http://www.rosseobservatory.ie) in Birr Castle Demesne is another partner of Ireland Array. The observatory is operated by the Solar Physics Group, Trinity College Dublin, led by Dr. Peter Gallagher. Ireland Array station IA003 is deployed at the Rosse Observatory (http://www.rosseobservatory.ie/instruments.php).

*Presentations:*

**Lebedev, S., C. Horan, P. Readman, A. Schaeffer, L. Collins, F. Hauser**, and **B. O'Reilly** (2011), Ireland Array: a seismic investigation of Ireland's evolution, seismicity and new energy resource potential, 54th Irish Geological Research Meeting, NUI, Galway, Ireland, 18-20 February.

**Lebedev, S., P. Readman, C. Horan, A. Schaeffer, L. Collins, M. Agius, F. Hauser, B. O'Reilly**, and **T. Blake** (2011), Ireland Array: Broadband seismic investigation of the lithospheric structure and evolution of Ireland and surroundings, Atlantic Ireland 2011, A Petroleum Conference Organised by PIP-ISPSG, Dublin, Ireland, 17 October.

## 6.2 Seismic anisotropy and deformation of southern Africa's cratons

*J. Adam, S. Lebedev*

Seismic anisotropy within the lithosphere of cratons preserves a record of their ancient assembly. In southern Africa, anisotropy across the Archean Kaapvaal Craton and Limpopo Belt has been detected previously by observations of SKS-wave splitting. Because SKS-splitting measurements lack vertical resolution, however, the depth distribution of anisotropy has remained uncertain. End-member interpretations invoked the dominance of either anisotropy in the lithosphere (due to the fabric formed by deformation in Archean orogenies) or that in the asthenosphere (due to the fabric formed by the recent plate motion), each with significant geodynamic implications.

In order to determine the distribution of anisotropy with depth, we measured phase velocities of seismic surface waves between stations of the Southern African Seismic Experiment. We applied two complementary measurement approaches, very-broadband cross-correlation and multimode waveform inversion. Robust, Rayleigh- and Love-wave dispersion curves were derived for 4 different sub-regions of the Archean southern Africa in a period range from 5 s to 250-400 s (Rayleigh) and 5 s to 100-250 s (Love), depending on the region. Rayleigh-wave anisotropy was determined in each region at periods from 5 s to 150-200 s, sampling from the upper crust down to the asthenosphere. Jackknife method was used to estimate uncertainties, and the F-test to verify the statistical significance of anisotropy.

We detected strong anisotropy with an N-S fast-propagation azimuth in the upper crust of the Limpopo Belt. We attribute it to aligned cracks, formed by the regional, E-W extensional stress associated with the southward propagation of the East African Rift. Our results show that it is possible to estimate regional stress from short-period,

surface-wave anisotropy, measured in this study using broadband-array recordings of teleseismic surface waves.

Rayleigh-wave anisotropy at 70-120 s periods shows that the fabric within the deep mantle lithosphere of the Limpopo Belt and northern Kaapvaal Craton is aligned parallel to the Archean sutures at block boundaries. This confirms that the blocks' lithosphere underwent pervasive deformation with suture-parallel flow during the Archean continental collisions and that the fabric created by Archean deformation is preserved within the lithosphere. Suture-parallel fabric is absent, however, in the deep lithosphere of the western Kaapvaal Craton, suggesting that it was not reworked in the collision with the craton's core, either due to its mechanical strength or because the collision mechanism was different from those that operated in the north. Anisotropy at periods greater than 120-130 s shows fast directions parallel to the plate motion and indicates shear-wave anisotropy in the asthenosphere.

The depth distribution of anisotropy revealed by surface-wave measurements comprises elements of both end-member models proposed previously: anisotropy in the asthenosphere shows fast-propagation directions parallel to the plate motion; anisotropy in the Limpopo and northern Kaapvaal lithosphere shows fast directions parallel to the Archean sutures. The distribution of SKS splitting orientations across southern Africa reflects anisotropic fabric both within the lithosphere (dominating the splitting beneath the Limpopo Belt and northern Kaapvaal Craton) and within the asthenosphere (dominating beneath the western Kaapvaal Craton).

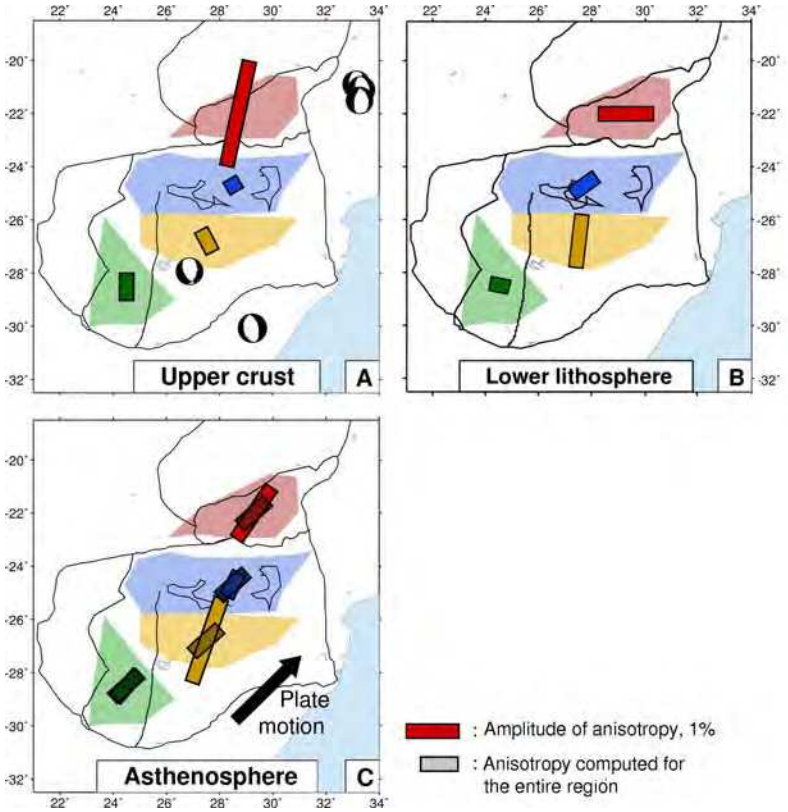



**Figure 1:** Azimuthal anisotropy of Rayleigh waves sampling primarily the upper crust (A), lower lithosphere (B) and asthenosphere (C). A: Fast-propagation directions of Rayleigh waves at 5-7 s periods. Focal mechanisms of earthquakes are plotted to indicate the regional tectonic stress. B: Fast-propagation directions at 80-120 s periods, with sensitivity primarily to the deep mantle lithosphere. C:

Fast-propagation directions at 130-160 s periods, with sensitivity primarily below 200 km. Grey bars: fast directions from the inversion for all-region-average anisotropy.

*Presentations:*

**Adam, J**., and **S. Lebedev** (2011), Layering of seismic anisotropy and deformation beneath South Africa from the upper crust to the asthenosphere, talk presented at EGU General Assembly, Vienna, Austria,3-8 April.

**Adam, J.,** and **S. Lebedev** (2011), Stratification of seismic anisotropy and deformation beneath South Africa, from the upper crust to the asthenosphere, poster presented at AGU Fall meeting, San Francisco, USA, 5-9 December.

## 6.3 Seismic study of the structure and dynamics of Tibet

*M. Agius, S. Lebedev*

The Tibetan Plateau formed as a result of the continental collision between India and Eurasia. In spite of numerous seismic studies to date, fundamental questions regarding the mechanism of the collision, such as how far north and how deep India subducts, remain unanswered. In order to investigate the lithospheric mantle architecture beneath Tibet, we measure inter-station phase velocities of seismic surface waves. Within the high plateau, phase velocities at short periods are anomalously slow, reflecting anomalously high thickness of the crust. At longer periods, surface waves sample the lithospheric mantle, including both Tibetan and subducted Indian lithospheres.

Our results show that West Lhasa (south west Tibet) is underlain by a fast (cold), cratonic-like lithospheric mantle whereas Central Lhasa is not. In central and northern Tibet the uppermost mantle has low average velocities, indicative of high temperatures. At greater depth beneath central and eastern Tibet, a high-velocity anomaly (>5%) occurs below the slow (warm) uppermost mantle, probably indicating subducted Indian lithosphere. Temperature estimates inferred from the Vs anomalies show that the subducted lithosphere is 300-820°C colder than the surrounding asthenosphere, consistent with the subduction of India beneath central and eastern Tibet.

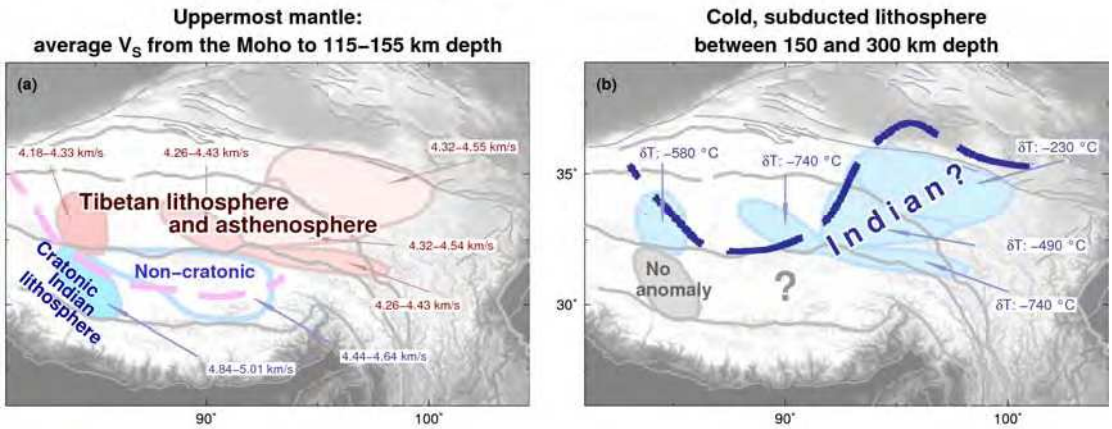



**Figure 2:** Shear-wave velocities and temperature estimates for the lithospheric mantle across Tibet, inferred from inversion of the new, broad-band surface wave dispersion measurements. (a) Uppermost mantle Vs (average between the Moho and 115-155 km); dashed thick pink line: the boundary between high-velocity (India) and low-velocity (Tibet) lithosphere at 110 km depth according to the global surface-wave tomography of Lebedev and van der Hilst (GJI 2008). (b) Cold, subducted lithosphere beneath Tibet. Thick dashed blue line: a +2.5% anomaly contour at 200 km depth, from the global surface-wave tomography. Shaded regions indicate high-velocity (cold; blue) and low-velocity (warm; red) anomalies at depth, constrained using the new dispersion measurements. Grey lines: major sutures.

*Presentations:*

**Agius, M.R.,** and **S. Lebedev** (2011), Crustal and mantle structure beneath Tibet, from shear-velocity profiles, 54th Irish Geological Research Meeting, NUI, Galway, Ireland, 18-20 February.

**Agius, M.R**., and **S. Lebedev** (2011), The crustal and mantle structure beneath Tibet, from shear-velocity profiles, Invited seminar, University of Malta, 4 March.

**Agius, M.R**., and **S. Lebedev** (2011), The shear velocity structure of the lithospheric mantle beneath Tibet, AGU Fall Meeting, Abstract T43A-2292, San Francisco, USA, 5-9 December.

**Lebedev, S., M.R. Agius**, and **A.J. Schaeffer** (2011), Shallow-Angle Subduction of the Indian Plate Beneath Tibet: New Seismic Images and Implications for the Evolution of the Plateau, AGU Fall Meeting, Abstract T51D-2363, San Francisco, USA, 5-9 December.

## 6.4 Structure and dynamics of the upper mantle: Global and regional-scale S-velocity tomography.

*A. Schaeffer, S. Lebedev*

The rapid recent expansion of global and regional seismic networks has paved the way for a new generation of tomographic models, with significantly improved resolution at global and regional scales. We constructed a new global model of shear velocity and azimuthal anisotropy in the upper mantle, down to the base of the transition zone. The model is constrained by an unprecedentedly large waveform dataset collected from over 2000 stations of GSN and affiliates, USArray, VEBSN, CNSN, PASSCAL experiments, and other networks with data available from IRIS and GFZ data centres. Applying the accurate and efficient automated multimode inversion of surface- and S-wave forms to this massive dataset, we generated linear constraints on elastic structure within approximate sensitivity volumes between individual source-receiver pairs, with respect to a 3D reference model. The full waveform inversions resulted in more than one million successful fits (one million seismograms), with structural information extracted from both the fundamental and higher modes. The linear equations were then simultaneously solved for a high-resolution, 3D model of shear velocity and azimuthal anisotropy in the upper mantle.

In continental domains, clearly identifiable boundaries between different tectonic features such as basins and relic mountain ranges are readily observable, as well as the signature of deep cratonic roots versus juvenile accretionary margins. Both active and fossil subduction zones are marked by slab signatures deep in the upper mantle and extending through the transition zone. In oceanic regions, largest mid-ocean-ridge anomalies indicative of melting terminate at depths of 100-120 km, with evidence for vertical flow in the upper mantle observed through a combination of $V_{SV}$, $V_{SH}$, and azimuthal anisotropy. Spatio-temporal evolution (cooling and thickening) of lithosphere away from the spreading ridges matches the signature expected from geodynamic and thermal modelling.

The resolution of global azimuthal anisotropy has been improved significantly, compared to earlier global tomography that utilized smaller data volumes. In ocean basins, as observed previously, fast-propagation directions align with paleo-spreading orientations at shallow depths within the lithosphere and modern plate motions at greater depths within the asthenosphere. In continental domains, both lateral

variations and radial layering of anisotropic fabrics are now resolvable at a smaller scale, for regional- and tectonic assemblage-scale domains.

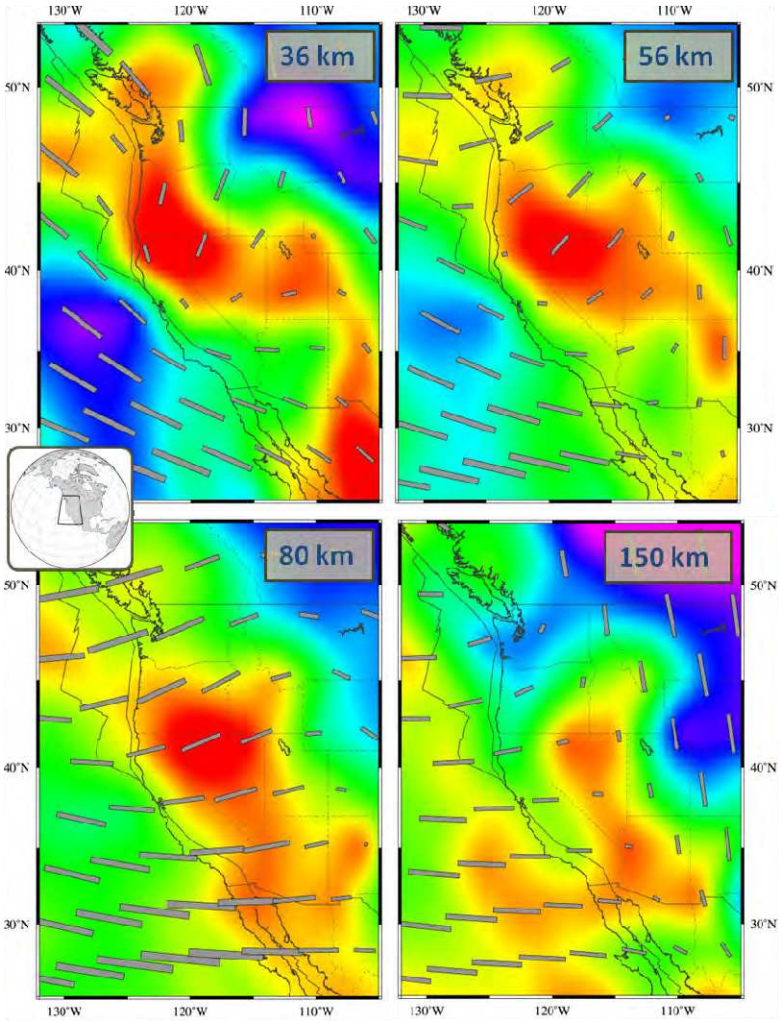



**Figure 3:** Isotropic and anisotropic shear velocity variations in Western North America. Colours correspond to isotropic variations of ±6%, while anisotropy magnitude is ±2% at 36 and 56 km depth, and ±1.5% at 80 and 150 km depth. Strong low velocity anomalies (red) underlie tectonically active Western North America at depths between 36 and 80 km. The transition from green to blue colours within the continent corresponds with the transition to stable, cratonic North America. Anisotropic variations at shallow depths change sharply at the coastline, between the continental and oceanic domains. A pronounced change in the orientation of anisotropic fabric is also observed at the boundary of the cratonic North America.

*Presentations:*

**Schaeffer**, **A.J**., and **S. Lebedev** (2011), Global and Regional Scale Seismic Tomography using Surface and S waveform inversion, EGU General Assembly, Abstract EGU2011-11651, Vienna, Austria, 3-8 April.

**Schaeffer**, **A.J.,** and **S. Lebedev** (2011), Anisotropic Structure of the Upper Mantle, Imaged with Surface and S Waveform Tomography, AGU Fall Meeting, Abstract S13C-04, San Francisco, USA, 5-9 December.

## 6.5 Geodynamic modelling of continental deformation

*C. Tirel, S. Lebedev, in collaboration with J.-P. Brun (Rennes), E. Burov (Paris VI)*

Subduction zones are factories that continually shape convergent plate boundaries and accrete new crust to the overriding continental plates. Arguably the most enigmatic products of these factories, high-pressure (HP) metamorphic belts comprise rock units that were regurgitated to the Earth's surface soon after their subduction to deep crustal and mantle depths. In the intensively studied Aegean back-arc domain in the Mediterranean, several HP belts can be related to the continuous subduction of the same African lithospheric plate, which indicates that their exhumation may be a transient and recurrent process. We use thermo-mechanical numerical simulations to show that successive subduction of multiple continental blocks—and the associated variations in the slab buoyancy and rollback rate—are responsible for the episodic rollback-exhumation cycles. Our modelling reproduces the major structural patterns and pressure temperature-time (PTt) paths of the HP rocks in different parts of the Aegean and elucidates a fundamental mechanism of HP exhumation.

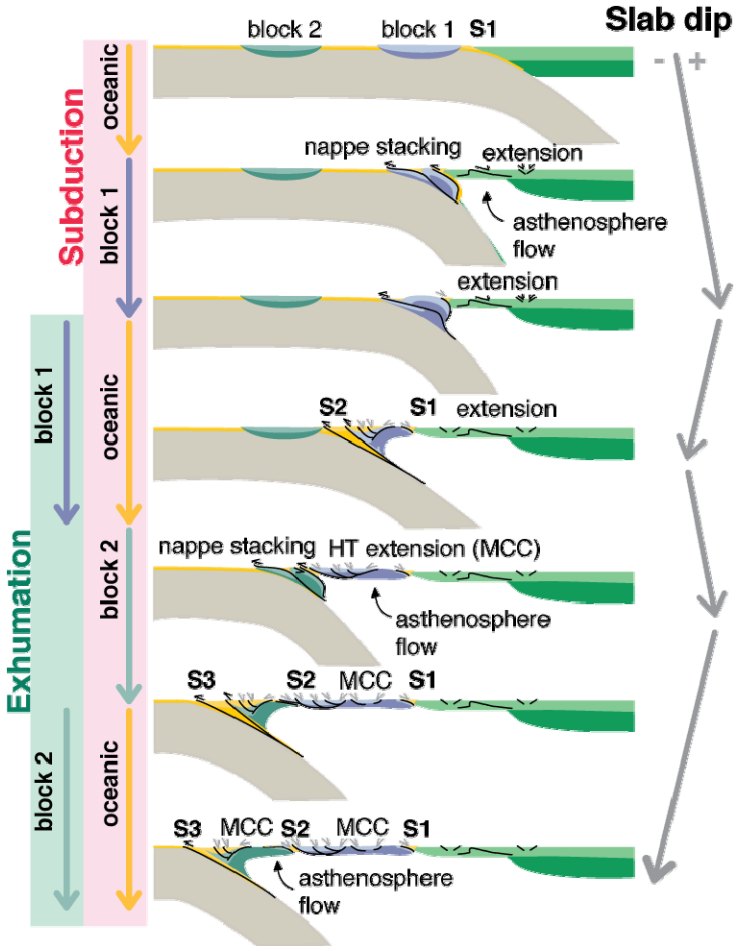



**Figure 1:** The relationship between the continental-block subduction and exhumation, slab dip changes and crustal deformation.

*Presentation:*

**Tirel, C.**, J.-P. Brun, E. Burov, and **S. Lebedev** (2011), Dynamics of subduction, accretion, exhumation and slab rollback: Mediterranean scenarios, 54th Irish Geological Research Meeting, NUI, Galway, Ireland, 18-20 February.

## 6.6 Structure and Deformation of the Eastern Mediterranean

*S. Lebedev, C. Tirel, E. Neenan (summer intern, TCD), M. Agius, A. Schaeffer*

The slow convergence of Africa and Eurasia has been accompanied by spectacular tectonic activity within the eastern Mediterranean. The evolution and retreat of subduction zones has brought about pervasive deformation of continental back-arc basins. Continental deformation in the eastern Mediterranean is at rates among the highest globally, and with diverse patterns and boundary conditions. Understanding of this deformation promises important new insights into the dynamics of continents, and numerous competing models have been put forward. The lack of consensus to date is in large part due to the paucity of observational constraints on the deformation and flow within the deep crust and lithospheric mantle.

Observations of seismic anisotropy provide constraints on deformation at depth. Array analysis of surface waves, in particular, can resolve variations in anisotropic fabric both laterally and as a function of depth. Recent seismic-anisotropy imaging indicates widespread diffuse deformation within the lithosphere, some of it with previously unknown patterns. Anisotropy shows the layering of finite strain in the crust and mantle. It reveals complex, depth-dependent flow patterns within the extending lithosphere and underlying asthenosphere.

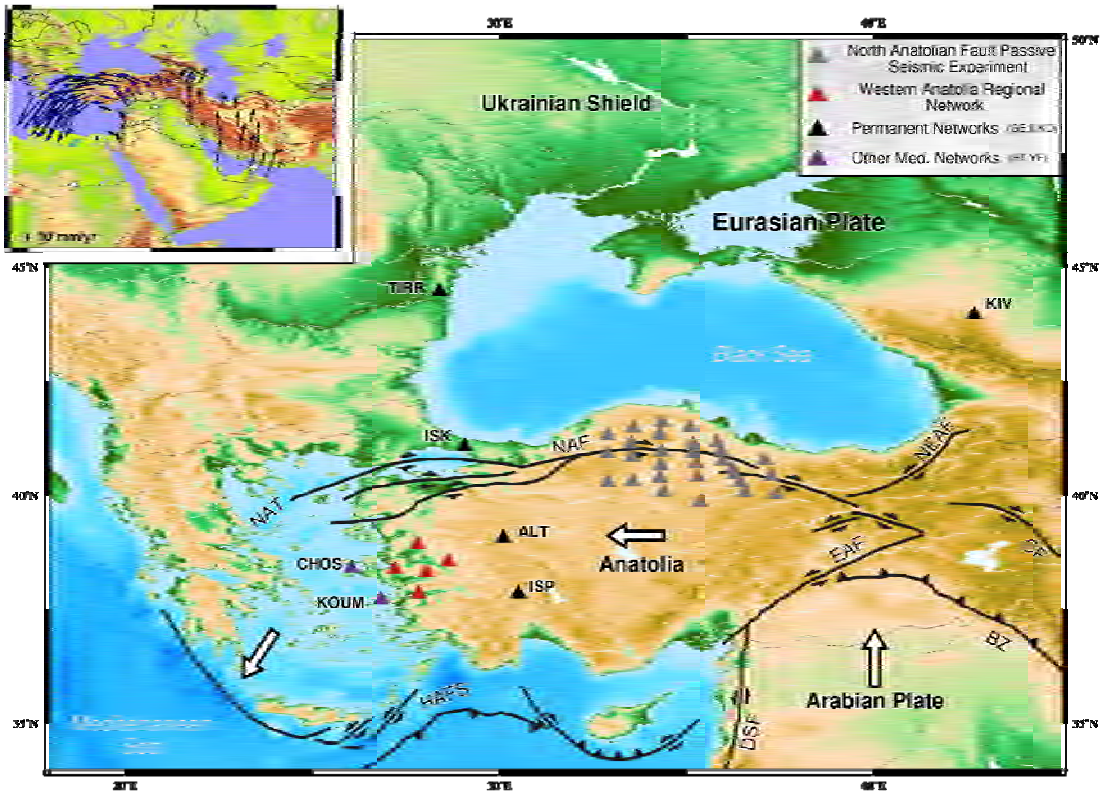



**Figure 1:** The tectonic framework of the Eastern Mediterranean and the locations of seismic stations used in the study of Neenan et al. (AGU 2011). Inset: regional surface motions given by GPS measurements.

The shear associated with the westward motion of Anatolia is localised at and near the North Anatolian Fault (NAF). Because the crustal and mantle deformation is three-dimensional, with strain patterns depth-dependent, it is difficult to determine the deformation mechanisms from surface observations alone. We measured phase velocities of seismic surface waves using seismic stations in eastern Mediterranean and inferred depth-dependent orientations of anisotropic fabrics—a record of deformation in the crust and mantle. We also used the measurements to determine S-velocity profiles, indicative of temperature within the lithosphere and, therefore, its

mechanical strength. The lithosphere gets warmer and thinner from the Black Sea (north of NAF) to central Anatolia (south of NAF). The fault is thus localised near the transition between mechanically strong and weak lithospheric blocks. The lower crust and mantle lithosphere beneath NAF show E-W, fault-parallel, distributed flow within an about 100-km wide zone. The underlying asthenosphere flows NE-SW, towards the retreating Hellenic Trench. Although the motion of lithospheric blocks is driven by the same trench retreat, it is influenced by lateral variations in the lithosphere's mechanical strength and is very different from the flow in the asthenosphere.

*Publication:*

Endrun, B., **S. Lebedev**, T. Meier, **C. Tirel**, and W. Friederich (2011), Complex layered deformation within the Aegean crust and mantle revealed by seismic anisotropy, *Nature Geoscience, 4*, 203-207.

*Presentations:*

Meier, T., B. Endrun, **S. Lebedev, C. Tirel**, and W. Friederich (2011), Layered deformation within the Aegean continental crust and mantle revealed by seismic anisotropy, Abstract EGU2011-12497, EGU General Assembly, Vienna, Austria, 3-8 April.

**Lebedev, S**. (2011), Seismic imaging of lithospheric structure and deformation in Europe and other continents, Invited seminar, University of Potsdam, Germany, 2 May.

**Lebedev, S**. (2011), Lithospheric structure and deformation, Invited seminar, University of Kiel, Germany, 4 May.

Meier, T., B. Endrun, **S. Lebedev, C. Tirel**, and W. Friederich (2011), Layered deformation within the Aegean continental crust and mantle revealed by seismic anisotropy. Fragile Earth: Geological Processes from Global to Local Scales, Associated Hazards & Resources, International Conference, Munich, Germany, 4-7 September.

**Neenan, E., M.R. Agius, A.J. Schaeffer,** and **S. Lebedev** (2011), Lithospheric Anisotropy and Deformation in Anatolia, Eastern Mediterranean: A Seismic Surface-Wave Study, Abstract T43E-2431, AGU Fall Meeting, San Francisco, USA, 5-9 December.

## 6.7 Structure and evolution of the Pacific lithosphere

*P. Lynch, A. Schaeffer, M. Agius, S. Lebedev*

This new project was initiated by Peter Lynch, a physics student from TCD, during his summer internship in the seismology group, co-supervised by Lebedev, Agius and Schaeffer.

The temperature contrast between the cold oceanic lithosphere and the hot asthenosphere beneath it is reflected in the pronounced drop in seismic velocities at the lithosphere-asthenosphere boundary. In addition to the immediate effect of temperature, other factors may also influence the observed seismic velocities, including partial melting or higher volatile content in the asthenosphere relative to the lithosphere. Because the temperature changes, partial melting and volatile content all have a strong effect on viscosity as well, their characteristics and relative significance have important implications for the models of the dynamics of the oceanic plates. We measured phase velocities of surface waves across central Pacific using pairs of permanent seismic stations and a combination of cross-correlation and multimode-waveform-inversion approaches. Robust, accurate Rayleigh- and Love-wave

dispersion curves in broad period ranges were averaged from tens to hundreds of one-event measurements. The dispersion curves were then inverted for isotropic-average shear-velocity profiles and radial anisotropy. Regional-scale stratification of azimuthal anisotropy was also constrained. The high accuracy and broad period ranges of the phase-velocity measurements and the small size and simplicity of the inverse problems that related them to shear velocities enabled us to determine particularly robust shear-velocity profiles, with implications for thermal and compositional models and, also, lateral variations in lithospheric properties, including those between hotspot-rejuvenated and normal-ocean lithosphere.

*Presentation:*

**Lynch, P., A.J. Schaeffer, M.R. Agius**, and **S. Lebedev** (2011), Robust Shear-Velocity Profiles Within Oceanic Lithosphere and Asthenosphere: Implications for Thermal and Compositional Structure, Abstract T31A-2319, AGU Fall Meeting, San Francisco, USA, 5-9 December.

## 6.8 Imaging Earth structure and anisotropy with seismic surface waves

*S. Lebedev*

The rheological behaviour of the lithosphere, a dynamic thermal boundary layer, shows large variations, radial, lateral, and in time. The coldest upper crust is brittle; the lower crust and lithospheric mantle will flow like viscous fluids when relatively warm but will resist deformation when cooled down. Below the lithosphere, the viscous asthenosphere undergoes continual, three-dimensional flow. The layered, evolving deformation within the lithosphere and asthenosphere thus creates a complex distribution of anisotropic fabric which varies in the 3 spatial dimensions as well as in its age. Surface-wave data, in particular that from dense arrays of broad-band seismic stations, can constrain both lateral and radial distributions of seismic structure and anisotropy in the entire lithosphere-asthenosphere depth range. Recent results are consistent with those given by other data types, including SKS-splitting and Pn-anisotropy data, where the sensitivity ranges of the different measurements overlap. Joint analysis of the data of different types is beginning to produce tighter constraints on anisotropic heterogeneity. Accurate mapping of lithospheric anisotropy helps to account for the shallow signal in the analysis of deep-mantle anisotropy. Combined with the geological record and geodetic data, the new, detailed models of structure and anisotropy of the lithosphere-asthenosphere system offer new insight into the dynamics and evolution of the lithosphere.

*Publications:*

Bartzsch, S., **S. Lebedev**, and T. Meier (2011), Resolving the lithosphere-asthenosphere boundary with seismic Rayleigh waves, *Geophys. J. Int., 186*, 1152-1164.

Becker, T.W., **S. Lebedev**, and M.D. Long (2011), On the relationship between azimuthal anisotropy from shear wave splitting and surface wave tomography, *J. Geophys. Res.*, accepted, November, 2011.

*Presentations:*

Afonso, J.C., Y. Yang, **J. Fullea, S. Lebedev**, and S. Zlotnik (2011), A 3D multi-observable probabilistic inversion method for the compositional and thermal

structure of the lithosphere and sublithospheric upper mantle, Abstract EGU2011-5209, EGU General Assembly, Vienna, Austria, 3-8 April.

Legendre, C., T. Meier, **S. Lebedev**, W. Friederich, and the EGELADOS Working Group (2011), Shear-wave velocity model of the European Upper Mantle, Abstract EGU2011-4961, EGU General Assembly, Vienna, Austria, 3-8 April.

Legendre, C., **S. Lebedev**, T. Meier, and W. Friederich (2011), Shear wave model of the European mantle, 7th TOPO-EUROPE Workshop, Davos, Switzerland, 6-9 October.

**Lebedev, S**. (2011), Seismic tomography: Imaging the structure and dynamics of the Earth, Invited seminar, Dublin City University, School of Physical Sciences, Dublin, Ireland, 27 October.

Afonso, J.C., **J. Fullea**, Y. Yang, W.L. Griffin, **A.G. Jones**, J. Connolly, **S. Lebedev**, and S.Y. O'Reilly (2011), 3D multi-observable probabilistic inversion for the compositional and thermal structure of the lithosphere and sublithospheric upper mantle, Abstract DI53A-02, AGU Fall Meeting, San Francisco, USA, 5-9 December.

### 6.9 Main collaborations

- University of Bergen, Norway (Profs. Henk Keers, Lars Ottemoller, Stephane Rondenay)
- University of British Columbia, Canada (Prof. Michael Bostock)
- University of Ottawa, Canada (Prof. Pascal Audet)
- University of Kiel, Germany (Prof. Thomas Meier, Dr. Christian Weidle)
- Ruhr University Bochum, Germany (Prof. Wolfgang Friederich)
- University College Dublin, Ireland (Prof. Chris Bean)
- Macquarie University, Australia (Drs. Juan Carlos Afonso and Yingjie Yang)
- University Paris VI, France (Prof. Evgeny Burov)
- University of Maryland, U.S. (Prof. Vedran Lekic)
- University of Southern California, U.S. (Prof. Thorsten Becker)
- Yale University, U.S. (Prof. Maureen Long)

## 7 Seismological and potential field activities

*Group Leader: Assistant Professor Brian O'Reilly*

### 7.1 PIMS (Porcupine Irish Margin Seismics)

*B.M. O'Reilly, P.W. Readman, and F. Hauser*

A paper was submitted to the Geological Society of London. This paper presents new, somewhat speculative, ideas regarding the late stage processes of continental crustal growth in Ireland that occurred about 400 million years ago. It is based on seismological results, recently obtained in DIAS and an extensive critical overview for the geological literature. The current model is remarkably consistent with the Raleigh-wave tomographic results (see ISUME), but challenges older concepts.

Using the results of recent seismic investigations of the upper continental lithosphere within the Caledonian/Variscan Fold Belt in southwest Ireland a geological model is developed for the late Caledonian/early Devonian accretion history of the crust. It is suggested that this geological model can explain a variety of geological phenomena.

These include the origin of the "Newer Granite" series in Britain and Ireland, the partial preservation of lower Devonian "Lower Old Red Sandstone" rocks, within the braided Caledonian fault network and the relatively low metamorphic grade of the Caledonian basement rocks, into which many of the granites are intruded. The proposed model (Figure 1) involves a process called "incipient delamination" where the mantle part of the lithosphere did not detach completely from the accreted crust during the late Caledonian to Acadian orogenic events.

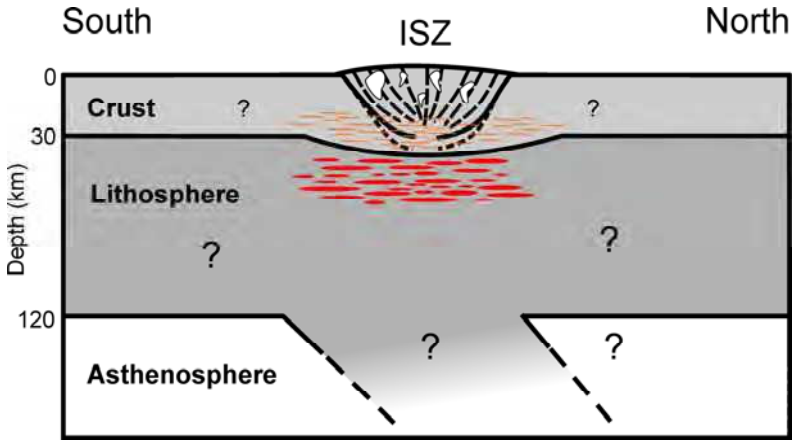



**Figure 1:** Schematic cartoon depicting a conceptual model for the development of fine seismic structure in the lower crust and sub-crustal mantle lithosphere. Iapetus Suture Zone (ISZ) marks the region where continental collision occurred (ca 400 Million years ago). White blobs - granites. Red lenses - mafic magma intrusions. Orange lines - late stage tectonic fabrics.

*Publications:*

**O'Reilly, B.M., F. Hauser,** and **P.W. Readman** (2011), The fine-scale seismic structure of the upper lithosphere within accreted Caledonian lithosphere: implications for the origins of the "Newer Granites", Submitted to *Journal of the Geological Society*, London.

## 7.2 TRIM (Tobi Rockall Irish Margins)

*B.M. O'Reilly, and colleagues from University College Dublin, the University of Ulster and Durham*

The continental margin offshore western Ireland offers an opportunity to study the effects of glacial forcing on the morphology and sediment architecture of a mid-latitude margin. High resolution multibeam bathymetry and backscatter data, combined with shallow seismic and TOBI deep-towed side-scan sonar profiles, provide the basis for this study and allow a geomorphological interpretation of the northwest Irish continental margin at a great level of detail. Several features, including submarine mass failures, canyon systems and escarpments, are identified in the Rockall Trough for the first time.

A new physiographic classification of the Irish margin is proposed and linked to the impact that glacial processes had across the region. Correlation of the position and dimensions of moraines on the continental shelf with the level of canyon evolution suggests that the sediment and meltwater delivered by the British-Irish Ice Sheet played a fundamental role in shaping the margin including the upslope development of some of the canyon systems. The glacial influence is also suggested by the variable extent and backscatter signal of sedimentary lobes associated with the canyons.

These lobes provide an indirect measurement of the amount of glaciogenic sediment delivered by the ice sheet into the Rockall Trough during last glacial maximum. None of the sedimentary lobes demonstrate notable relief, indicating that the amount of glaciogenic sediment delivered by the British-Irish Ice Sheet into the Rockall Trough was limited. A general model for the glaciogenic development of the continental slope and its relationship to climate change is put forward, based on an image processing approach.

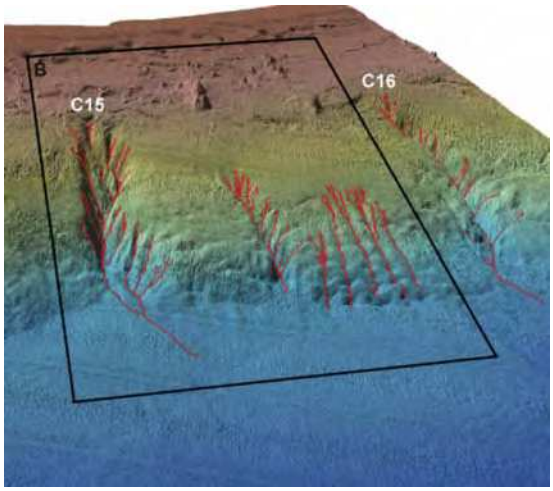



**Figure 2:** Digital elevation image of canyon systems (red) on the Porcupine Bank margin (up to 2000 m water depth) and cold-water carbonate mound build-ups along the continental shelf (600 m water depth).

*Publication:*

Sacchetti, F., S. Benetti, A. Georgiopoulou, P.M. Shannon, **B.M. O'Reilly**, P. Dunlop, R. Quinn, and C.Ó Cofaigh (2012), Deep water geomorphology of the formerly glaciated Irish margin from high-resolution marine geophysical data, *Marine Geology*, **291-294**, 113-131.

## 7.3 ISLE (Irish Seismological Lithospheric Experiment)

*P.W. Readman and B.M. O'Reilly, with J.P. O'Donnell and E. Daly, NUI Galway*

The paper describing the results of jointly inverting teleseismic P-wave delay times with the long wavelength satellite-derived GRACE gravity anomaly in Ireland was published in Geophysical Journal International. The paper addressed the disconnect that exists in the geophysical literature between a lithosphere that is pervaded by Palaeozoic signatures and an asthenoshere purportedly dominated by more recent Tertiary structure related to the Iceland Plume.

We suggest that the density and seismic velocity anomalies imaged in the lithosphere (Figure C) result from compositional variations, rather than from thermal contrasts driven by the Iceland Plume. These compositional variations could be due to either terrane accretion resulting from the closure of the Iapetus Ocean, or frozen decompressional melt generated during the opening of the North Atlantic Ocean, or frozen Iceland Plume related magmatic intrusions, or a combination of any or all of these effects. The continuation of the observed anomalous structure across the lithosphere-asthenosphere boundary (Figure 3) is interpreted as reflecting sub-lithospheric small-scale convection initiated by the lithospheric compositional contrasts. Overall, the velocity and density models for the uppermost mantle

demonstrate that Tertiary asthenospheric structure is likely to be intimately related to lithospheric structure.

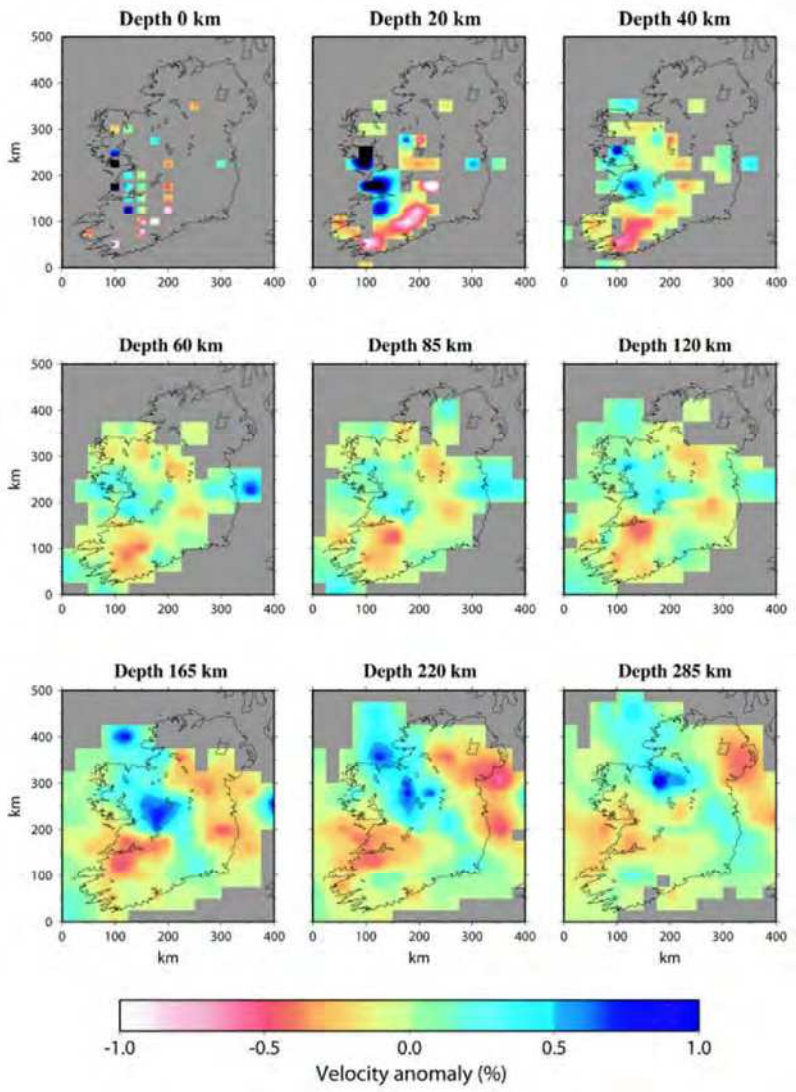



**Figure 3:** P-wave velocity depth slices retrieved by joint inversion of teleseismic relative arrival time residuals and GRACE long-wavelength satellite-derived gravity.

*Publication:*

O'Donnell, J.P., E. Daly, C. Tiberi, I.D. Bastow, **B.M. O'Reilly, P.W. Readman,** and **F. Hauser** (2011), Lithosphere-asthenosphere interaction beneath Ireland from joint inversion of teleseismic P-wave delay times and GRACE gravity, *Geophys. J. International, 184*, 1379-1396, doi: 10.1111/j.1365-246X2011.04921.x

## 7.4 ISUME (Irish Seismological Upper Mantle Experiment)

*P.W. Readman, B.M. O'Reilly, F.Hauser and G. Polat*

The Irish landmass was formed in the Caledonian Orogeny during the Palaeozoic assembly of Pangea, about 400 Ma. The associated closure of the Iapetus Ocean is recorded in the major, NE–SW trending Iapetus Suture Zone that dominates the tectonic set-up of Ireland today. Fabric within deep crustal rocks beneath sutures preserves a record of deformation during and after the continental collisions.

Rayleigh-wave phase velocities for Ireland have been measured by using a two-station technique that combines cross-correlation with an efficient scheme of filtering and windowing of the signal to provide accurate measurements in broad period ranges. Seismograms recorded by the 22 temporary broadband stations deployed during the ISLE and ISUME projects and two permanent DIAS seismic stations were used to provide phase-velocity curves for 43 different paths between station pairs. The data were inverted for phase-velocity maps including azimuthal anisotropy.

Isotropic phase-velocity heterogeneity of around 2% was observed (Figure 4) and reflects the moderate crustal thickness variability and seismic velocity variations derived from the results of our previous controlled source experiments. Anisotropy of Rayleigh waves shows a NE–SW fast-propagation direction for periods of 10 to 20 s, at which Rayleigh waves sample primarily the middle and lower crust (Figure 4). While this is not surprising for shorter periods (10 s) that are sensitive to structure in the upper-middle crust, at longer periods (15–20 s) that resolve middle to lower crustal depths, the orientation is identical. This indicates that anisotropic fabrics with a Caledonian orientation persist throughout the entire crust.

The NE-SW trend of the deep-crustal anisotropic fabric is parallel to tectonic trends, in particular to the Iapetus Suture Zone, which indicates that suture-parallel flow in the mid-lower crust accommodated the continental collision. The apparent preservation of the Caledonian-age fabric shows that the deep crust in Ireland was neither stretched by the NW-SE extension associated with the opening of the North Atlantic, nor modified significantly by the Cenozoic magmatism in the region. The study shows that since early Carboniferous time, the Irish crust has remained relatively stable, with little subsequent modification.

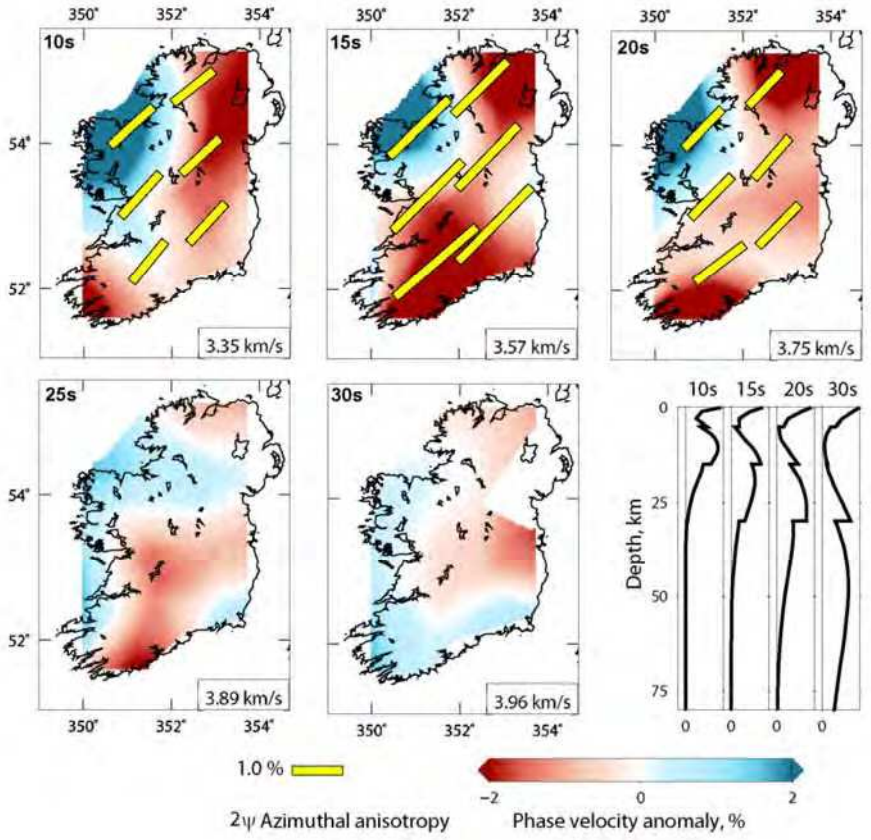


**Figure 4:** Tomographic maps of Rayleigh-wave phase velocities at different periods. The period and reference phase velocity are indicated in the upper left and lower right corners of the frames, respectively. The isotropic anomalies are shown in the background using the colour scale. Yellow sticks show the fast-propagation directions and strength of azimuthal anisotropy. Fréchet derivatives of Rayleigh-wave phase velocities at 10, 15, 20 and 30-s periods with respect to shear speeds at depth, computed for an (Ireland-like) model with a 30-km thick crust, are shown in the bottom right of the figure.

*Publication:*

**Polat, G., S. Lebedev, P.W. Readman, B.M. O'Reilly,** and **F. Hauser** (2011), Anisotropic Rayleigh-wave tomography of Ireland's crust: Implications for crustal accretion and evolution within the Caledonian Orogen, *Geophysical Research Letters*, **39**, L04302, doi:10.1029/2012GL051014.

*Presentations:*

**Polat, G., S. Lebedev, P. W. Readman, B.M. O'Reilly**, and **F. Hauser** (2011), Surface-Wave Tomography in Ireland, Irish Geological Research Meeting, NUI Galway, Ireland, 18-20 February.

**Lebedev, S., C. Horan, P.W. Readman, A.J. Schaeffer, L. Collins, F. Hauser,** and **B.M. O'Reilly** (2011), Ireland Array: a seismic investigation of Ireland's evolution, seismicity and new energy resource potential, Irish Geological Research Meeting, NUI Galway, Ireland, 18-20 February.

**Lebedev, S., P.W. Readman, C. Horan, A.J. Schaeffer, L. Collins, M. Agius, F. Hauser, B.M. O'Reilly,** and **T.A. Blake** (2011), Ireland Array: Broadband seismic investigation of the lithospheric structure and evolution of Ireland and surroundings, Atlantic Ireland 2011, A Petroleum Conference Organised by PIP-ISPSG, Dublin, Ireland, 17 October.

## 7.5 NAPSA (North Atlantic Petroleum Systems Assessment group)

*B.M. O'Reilly, and colleagues from Memorial University, Newfoundland and University College Dublin*

Work on a comparative study of the conjugate Irish and Canadian continental margins and sedimentary basins was progressed. 3-D gravity inversion methods (using the same model parameterisation) were used to generate models of sedimentary basin and crustal structure in order to compare the conjugate margin geometries.

Regionally-constrained 3-D gravity inversion results on the Orphan Basin/Flemish Cap and the Irish Atlantic conjugate continental margins are compared in order to investigate crustal structure, early rifting history and geological evolution of this part of the North Atlantic. The full-crustal density anomaly distributions provide some of the first depth images of how rifted structures compare along and across these conjugate margins. Broad similarities in crustal structure are identified with some noticeable differences, linked to rifting and crustal stretching processes. Extreme crustal thinning (stretching factors >3.5) is indicated beneath much of the southern Porcupine Basin, the western half of West Orphan Basin, the eastern half of Jeanne d'Arc Basin, the southeastern half of East Orphan Basin and in pockets beneath Rockall Basin.

This appears to have resulted in the serpentinization (and possible exhumation) of mantle lithosphere on the Irish Atlantic and Flemish Cap margins but not beneath Orphan Basin. A simple evolution model is proposed for the early stages of rifting between the margins. It is suggested that ancient orogenic sutures played an important

role in controlling the northward migration of rifting and the rotation and displacement of Flemish Cap out of Orphan Basin. A paper on the results has recently been submitted to the Geological Society of London.

Two workshops on the "Plate Reconstruction Project" of the North Atlantic region between Ireland and Newfoundland were held in St John's, Newfoundland (June 2011) and in Dublin (October 2011). The project uses recently acquired high quality propriety multi-channel seismic data sets together with magnetic and gravity data. These data will be used to constrain a model for the opening of the North Atlantic Ocean from about 200 million years ago. They will provide a preliminary model of how the entire petroliferous conjugate basin system works.

*Publications:*

Welford, K.J., P. M. Shannon, **B. M. O'Reilly**, and J. Hall (2011), Comparison of lithospheric density and Moho structure variations across the Orphan Basin/Flemish Cap and Irish Atlantic conjugate continental margins from constrained 3-D gravity inversions, Submitted to *Journal of the Geological Society*, London.

*Presentations:*

**O'Reilly, B.M.**, P.M. Shannon, J. Kim Welford, and J. Hall (2011), WARRP seismic acquisition offshore Ireland and Newfoundland: ISPSG PROJECT ISO9/06, 2011 North Atlantic Petroleum Assessment Conference, St John's, Newfoundland, Canada, 15-16 June.

**O'Reilly, B.M.**, P.M. Shannon, **P.W. Readman,** J. Kim Welford, and J. Hall (2011), Seismic acquisition: southwest Ireland to Porcupine Abyssal Plain: ISPSG PROJECT ISO9/06 (PHASE1). 2011 North Atlantic Petroleum Assessment Conference, St John's, Newfoundland, Canada, 15–16 June.

Welford, J.K., P.M. Shannon, **B.M. O'Reilly,** and J. Hall (2011), Lithospheric density variations and Moho structure of the Irish Atlantic continental margin from constrained 3-D gravity inversion. 2011 North Atlantic Petroleum Assessment Conference, St John's, Newfoundland, Canada, 15–16 June.

Welford, J.K., P.M. Shannon, **B.M. O'Reilly,** and J. Hall (2011), Comparison of lithospheric density and Moho structure variations across the Orphan Basin/Flemish Cap and Irish Atlantic conjugate continental margins from constrained 3-D gravity inversions. 2011 North Atlantic Petroleum Assessment Conference, St John's, Newfoundland, Canada, 15–16 June.

**O'Reilly, B.M.** (2011), Reconstruction of the Irish and Newfoundland continental margins, NAPSA Workshop, Dublin, Ireland, 15-16 October.

**O'Reilly, B.M.,** K. Welford, and P. Shannon (2011), Proposed new WARRP surveys offshore both Ireland and Canada, Atlantic Ireland Conference, Dublin, Ireland, 17 October.

**Lebedev S., C. Horan, P.W. Readman, L. Collins, F. Hauser,** and **B.M. O'Reilly** (2011), Ireland Array. A seismic investigation of Ireland's evolution, seismicity and new energy potential, Atlantic Ireland Conference, Dublin, Ireland, 17 October.

## 7.6 Collaborations

- UCD School of Geological Sciences: ISUME, TRIM, PIMS
- Applied Geophysics Unit, NUI Galway, ISUME
- University of Ulster (Colraine), TRIM

- Memorial University, St Johns, Newfoundland, NAPSA
- University of Liverpool, NAPSA
- University of Durham, TRIM

# 8 Irish Geoscience Graduate Programme (IGGP)

Director: Professor Alan G. Jones
Co-ordinator: Professor Ben Kennedy
Administrator: Ms. Caroline Moloney

The calendar year 2011 saw the very successful completion of the Pilot Year of the IGGP (www.iggp.ie), and the launch of the second year. In addition, the IGGP Administrator, Caroline Maloney, was hired to take the IGGP through the next four academic years.

The Second Year of the Irish Geoscience Graduate Programme (IGGP) is running smoothly, with the appointment of Caroline Moloney as the Administrator who will run the programme for the next four academic years.

The website (www.iggp.ie) has been updated and continues to be added to, with upcoming new courses being added. This provides details of the programme, modules, presenters, costs for outsiders and procedures for registration.

## 8.1 Module Offerings

Seventeen (17) modules were available in 2011-2012 and while some ran in first Semester, 2011/12, most of these have run or are scheduled to run in 2012 with three planned to run in 2013. There are additional new modules about to be added for 2013 (Please consult attached document for more details of same).

Six (6) are definitely to go ahead representing 60 individual registrations for a total of 300 ECTS credits.

## 8.2 Resource Issues

At a meeting with the Director and Assistant Director of GSI it was agreed that some funds could be used to pay postdoctoral fellows to present modules and to assist in laboratory operations. It was also agreed that travel and B&B costs would be covered where appropriate from the Overhead.

It has been agreed that IGGP will charge postgraduate students not registered at an Irish institution Euro25 per ECTS credit and others who are not postgraduate students but may wish to attend modules Euro250 per ECTS credit.

November 2011, the Co-ordinator and Administrator travelled to Universities affiliated with this programme to request further commitment from Professors, Senior Lecturers and Post Docs to present additional courses during the 2012 – 2015 period of the Irish Geoscience Graduate Programme. All have been very positive and have given commitments, despite the grave current financial situation and additional courses are being added, which are attracting overseas students as well as Irish postgraduates, which is most encouraging.

## 8.3 Presentations and attendance at other meetings

December 2011, the Coordinator and Administrator attended the CHIGI meeting (Committee of Heads of Irish Geosciences Institutes) with presentation update about the progress of IGGP 2010-2011.

The Administrator has arranged with the organizers of the Dublin City Of Science 2012 Festival to include details about IGGP in the *Partner Conference Calendar* with a possibility of a presentation also as schedule being finalized.

The Coordinator will attend the 54th Irish Geological Research Meeting (*IGRM*), which will be held in NUI Galway on 18th-20th February 2012, and an IGGP Report presentation has been scheduled during lunchtime on February 18.

### 8.4 Mid-Term Review:

The Coordinator met with the panel organised by Indecon to review the mid-term progress of the Griffith Awards in August. This provided the opportunity to summarise progress and to explain the reasons for the slow start of the programme including the frustrations compounded by the paralysis in the universities.

## 9 The Irish National Seismic Network (INSN)

*Experimental Officer Thomas Blake*

A new permanent seismic station, the 5th in the INSN, code name IWEX, was opened in Carrickbyrne Co Wexford and is transmitting data successfully in realtime to DIAS and to the international seismic agencies via our seedlink server. Noise tests were carried out in the Cooley peninsula in Co Louth in preparation for the selection of a permanent seismic station for this area station code ILTH. Blake attended the ORFEUS Workshop in Lisbon, Portugal, May 24- 27, 2011.

There was significant public interest in the role of the Irish National Seismic Network following the devastating earthquake in Japan on March 11th, 2011. Blake gave numerous radio, TV and print media interviews on the recording of this earthquake by the INSN.

July 26-27, Blake visited Geological Survey of Northern Ireland GSNI, and cooperated in site reconnaissance with colleagues from GSNI and BGS Edinburgh with a view to establishing 2 new permanent seismic sites in Northern Ireland.

Andrew Schaeffer continued the webpage development of the earthquake event catalogue page with automatic update within 10 minutes of an event occurring above Mag 6 on the Richter Scale.

Blake gave a Brown Bag seminar in TCD entitled “The Irish National Seismic Network (INSN), new developments and directions”.

Because the operation of the INSN is dependent on seiscomp3 software for event detection and analysis, Blake and P. Galland attended the Seiscomp3 Users Group meeting in Potsdam, Germany, September 19 - 22.

Blake also visited the International Seismological Centre at Thatcham in October 28th, one of the agencies with whom we cooperate with data exchange. Blake was the invited speaker at the ADLEC Conference in Limerick with a talk entitled “The Irish National Seismic Network (INSN) - A Wave of Scientific Opportunity“, in November 10th, 2011

## 10 CTBTO - Comprehensive Nuclear Test Ban Treaty Organisation, National Data Centre (NDC).

*T. Blake*

Work on the development of the National Data Centre located in Hut 2 continues, with the installation of the framework for the video wall and the installation of the associated computer materials and installation of the software. Various external remedial works have taken place on the building including painting and relocation of electrical supply. Work is also ongoing on the design and manufacture of appropriate signs for the building.

**Figure 1:** Jari Kortstrom NDC Finland working with Philippe Grange at NDC installation.

Blake attended the Working Group B CTBTO, Meeting in Vienna in February and September 2011.

At the CTBTO Science and Technology 2011 Conference in Vienna, June 8 – 12, Blake attended and presented a talk entitled "Educational outreach as a capacity development strategy, using the Irish example, Seismology in Schools, Dublin Institute for Advanced Studies (DIAS) Outreach Programme".

June 25 - July 9, Blake took part in CTBTO Field Exercises for Surrogate On-Site Inspectors in Vesprem, Hungary.

On October 13, the first CTBTO Mgt Meeting was held in DIAS to plan for the official of the NDC, Ireland in June 2012.

From October 16 – 22 there was a visit by Dale Roblin, Data Analyst in the Intentional Data Center, Vienna, to DIAS to help with the set up of the National Data Center in the School of Cosmic Physics.

**Figure 2:** Dale Roblin IDC Vienna working at the NDC, Ireland, installation in DIAS

Following increasing contact with the National Data Centre, UK, Blake as Head of the NDC Ireland visited the UK NDC at the UK Atomic Weapons Establishment at Blacknest, from October 26 – 28, 2011.

# 11 Collaboration with wider research community

## 11.1 Visitors

- Dr. Alan D. Chave, (Woods Hole Oceanographic Institution), January 10-14, 2011.
- Dr. Stewart Fishwick, (U. Leicester), May 25-27, 2011.
- Prof. Frederik Simons (Princeton University), August 11, 2011.
- Prof. Thomas Meier, Dr. Christian Weidle (University of Kiel), November 21, 2011.
- Prof. Stephane Rondenay (University of Bergen), November 23-24, 2011.
- Jari Kortsrom, data analyst with the National Seismic Agency, Helsinki, Finland, December 4–9, 2011
- Reinoud Sleeman, Director International Data Acquisition, ORFEUS, De Bilt, Netherlands December 11–14, 2011.

# 12 Public outreach: Seismology in Schools (Seismeolaíocht sa Scoil) Project

*T. Blake*

Grace Campbell started work as SIS coordinator assistant on a temporary contract for six months. In February a SIS Workshop was held in DIAS for 4 personnel from the Copper Coast Geopark in Bunmahon, Waterford, the first geopark to join the project.

Seismology in Schools helped to celebrate YURI Day, in the Temple Bar region of Dublin on April 12$^{th}$, bringing science to the streets of Dublin as a celebration of the 50th anniversary of the first manned space flight by Russian cosmonaut Yuri Gagarin.

Megan Heather, a Student at University of Plymouth, England, came to DIAS in February for one week work experience working on seismic issues and SIS.

DIAS personnel gave a SIS workshop in Waterford Institute of Technology and a lecture to students at the college.

Campbell and Heather developed Social Network pages on Twitter and Facebook for the SIS project.

Prof. Gerry Wrixon donated a SIS seismometer to St. Coleman's Secondary School, Fermoy, Co Cork, the latest to join the SIS project.

In October 5-7, Blake attended the SIS meeting in BGS, Keyworth, UK, to discuss strategy for the development of seismology education with UK and US colleagues.

**Figure 1:** Tom Blake at the SIS Meeting, BGS, Keyworth, UK

As part of Science Week, Blake delivered an address on '**Seismology in Schools**' in the Tralee Education Training Center and installed 2 seismometers at Mount Hawk School Tralee and at Colaiste na Scelige, Caherciveen Co Kerry. There are now 60 schools, geoparks and universities involved in the project.

Meetings were held during the year with Anna Walsh of the Curriculum Development Board to discuss the late proposal in the Draft Syllabus of Leaving Cert Honours Physics and the inclusion of seismology.

*Presentation:*

**Blake, T.,** and **G. Campbell** (2011), Educational outreach as a capacity development strategy, using the Irish example, seismology in schools, Dublin Institute for Advanced Studies (DIAS) Outreach Programme, CTBTO Science and Technology 2011 Meeting, Vienna, Austria, 8-12 June.

# 13 Short Courses, Workshops and Seminars

## 13.1 Short Courses

### 13.1.1 Time Series Analysis Short Course, April 11 - 15, 2011

Professor Gary Mitchum of the University of Southern Florida gave a Short Course in DIAS on Time Series Analysis. The course was originally conceived for DIAS students, but was extended to allow others to attend as part of the IGGP. There was an astounding response, with originally 65 registrants. Some 45 people completed the course, including not only national and international geoscientists but Irish astronomers and meteorologists.

### 13.1.2 Seismology (for Non-Seismologists) in the Investigation of Earth's Crust and Upper-Mantle. 17-20 May 2011

Dr. Mark Muller presented a Short Course on Seismology (for non-seismologists) under the auspices of the IGGP.

### 13.1.3 Lecture courses on potential field theory and continuum mechanics

In the summer term 2011, Prof. Martinec presented a semester course (it consists of 15 lectures of 2.5 hour duration):

- Earth's Gravity Field - Boundary-Value Problems (for Ph.D. students and post-docs at DIAS)

In 2011, two semester courses (each course consists of 15 lectures of 2.5 hour duration):

- Continuum Mechanics - Basic Principles (for undergraduates and Ph.D. students at the Charles University in Prague)
- Continuum Mechanics - Thermodynamics (for undergraduates and Ph.D. students at the Charles University in Prague)

## 13.2 Workshops

### 13.2.1 MT 3D Inversion Workshop II, DIAS, March 30 - April 1, 2011

For the second time, DIAS held a workshop on MT 3D inversion with 29 participants from academia and industry from across the globe (http://www.dias.ie/mt3dinv2/). Forward and inversion test models were designed and given to the participants prior to the workshop to model/invert. Therefore, during the workshop the various results were basis for comparison and discussion of codes and inversion techniques as well as the influence of the individual person using it (code developer as well as 'normal user'). A few case studies were presented, the current state of the art and future challenges and improvements were discussed. The workshop was financially supported by DIAS as well as three industry sponsors (EMGS, WesternGeco and Zonge). The workshop was live-broadcasted via internet and also video taped for later downloading of the talks.


A publication to summarise both workshops (2008 and 2011) is in preparation and submission is intended to Geophysical Journal International in March/April 2012.

### 13.2.2 ***ThermoDynaMix-III Workshop, November 2 - 4, 2011.***


The ThermoDynaMix-III workshop (http://www.dias.ie/ThermoDynaMixIII/) was the third in the series of small, focused workshops bringing together the world's experts in their relevant fields focused on the pressing need within the Solid Earth Geophysics community for publicly available, reliable, and internally consistent thermodynamic databases for mantle minerals and their associated software for geophysical-petrological modelling. More details can be found at the following web site: http://www3.imperial.ac.uk/earthscienceandengineering/research/geophysics/earthstructure/thermodynamix

Two workshops have been held previously, and were attended by experts from different but complementary areas such as experimental petrology, seismology, other mantle-scale geophysics, theoretical thermodynamics, and numerical modelling working on problems associated with physical properties of mantle assemblages. In each case there were 25-30 attendees.

The first workshop was held on 10-12 April, 2006 in Oslo (Norway), and the call is available on the web at: http://folk.uio.no/ninasim/Cr_results.html. The second workshop was held on 14-16 September, 2008 in Barcelona (Spain), and the initial call is available at: http://web.mac.com/sgoes/iWeb/Site/ThermoDynaMixII.html.

The ThermoDynaMix III workshop took place from the afternoon of Wednesday 2nd November to the evening of Friday 4th November in the Dublin Institute for Advanced Studies. It consisted of a set of tutorials, three keynote talks, nine short talks grouped into three broad sessions, about 15 posters, and break-out discussion sessions (as well as a social program facilitating informal discussions in the very nice city of Dublin). It was attended by >30 people with a wide range of backgrounds, spanning mineral physics, petrology and geophysics, including senior scientists with key relevant expertise and a substantial number of young researchers, from 11

different countries. In addition, 10 PhD students from DIAS attended. The diversity and multidisciplinarity of the group led to numerous and lively discussions, with a good focus on how we can work together towards achieving the objectives of the workshop.

Travel grants were provided for the three keynote speakers Jay Bass (University of Illinois, Urbana-Champaign), David Mainprice (Université Montpellier), and Paul Asimow (CalTech). A web site was created for the Workshop (http://www.dias.ie/ThermoDynaMixIII/index.html), containing all relevant information about the Workshop's objectives, registration fees, travel information, list of participants, etc. A summary of this report will be posted on the workshop web site.

### 13.2.3 Seismic Imaging Workshop, DIAS, November 22-23, 2011

A two-day workshop on a new collaborative work by seismologists from the University of Bergen, Norway (Profs. Henk Keers, Lars Ottemoller, Stephane Rondenay), University of Kiel, Germany (Prof. Thomas Meier, Dr. Christian Weidle) and DIAS (Sergei Lebedev and his group). The focus of the workshop was on the development and application of new seismic imaging methods.

## 13.3 Seminars

- 14 January – Dr. A.D. Chave (Woods Hole Oceanographic Institution, USA): "A Tale of Three Patents".
- 24 March – Drs. D. Chew and I. Sanders (TCD, Ireland): "High-pressure metamorphism in 475 Ma arc-continent collision in NW Ireland: can geological observations ground-truth the results of numerical modelling?".
- 29 March – Dr. T. Kalscheuer (ETH Zurich, Switzerland): "A new object-oriented inverse code with two case examples".
- 11 April – Prof. V. Lekic (Brown University in Rhode Island, USA): "Dramatic lithospheric thinning beneath rifted regions of Southern California".
- 26 May - Dr. S. Fishwick (University of Leicester, UK): "Imaging lithospheric structure beneath the oceans and continents - Surface wave studies of Africa and the Atlantic Margin".
- 2 June – Drs. B. Higgs and P. Dowdall (UCC, Ireland): "Time and Tides: Messages from a receding Moon".
- 3 June – Dr. P. Nee (Cornell University, USA): "Understanding the slip characteristic of the San Andreas fault in southern California".
- 7 June – Dr. L. MacGregor (OHM Ltd., Aberdeen, UK): "Integrating Well Log, Seismic, and CSEM Data for Reservoir Characterization".
- 8 June - Dr. M. Fernàndez (The Institute of Earth Sciences Jaume Almera (CSIC), Barcelona, Spain): "Geothermal Energy: origin and prospecting".
- 15 July – Mr. B. Alexander (University of Adelaide, Australia): "Preliminary results on: 3D MT Inversion through Evolution of Ellipsoid Functions".
- 11 August – Prof. F. Simons (Princeton University, USA): "Promoting Sparsity and Localization in Geophysical Inverse Problems".

- 29 August – Mr. G. Menzel-Jones (University of British Columbia, Canada): "Seismoelectric Modelling of the Flux-Normalized P-SV-TM Propagation Mode".
- 4 October – Dr. T. Korja (Oulu University, Finland): "Old, boring, resistive Fennoscandia?".
- 12 October – Dr. B. Hobbs (MTEM Ltd, Edinburgh, UK): "Risk and Reward: MTEM Story".
- 23 November – Dr. S. Rodenay (University of Bergen, Norway): "A seismological perspective on water in subduction zones".
- 1 December - Prof. C. Mudge (University of Adelaide, Australia): "Evolving Inversion Methods in Geophysics with Cloud Computing".

# 14 Exhibitions

## 14.1 BT Young Scientist Exhibition Jan 2011.

The School of Cosmic Physics participated in the BT YSE this year with our displays on earthquakes proving to be very popular with both the students and public alike. We had a very large number of visitors to the stand which was very ably manned by our PhD students to help answer queries.

**Figure 1:** BT Young Scientists Exhibition; DIAS staff explaining seismology

# 15 Miscellanea

*T. Blake*

Blake gave a series of interviews following on from the devastating earthquake in Japan which was recorded by the Irish National Seismic Network stations throughout the country:

- Drivetime Radio RTE, with Mary Wilson - 11th March 2011
- Ireland AM TV3 interview - 14th March 2011
- BBC Northern Ireland News Affairs Programme - 14th March 2011
- Sean Doherty Show Highland Radio - 15th March, 2011
- Galway Independent - 23rd March 2011

*A.G. Jones*

- Member, *Royal Irish Academy*
- Member, *Committee of Heads of Irish Geoscience Institutions*
- National Correspondent, *International Association of Geomagnetism and Aeronomy*
- Member, *Royal Irish Academy's Geosciences Committee*
- Member, *Geological Survey of Ireland's Consultative Committee*
- Member, *European Science Foundation's Life, Earth and Environmental Sciences Committee*
- Member, *Geo-Electromagnetism Committee, Chinese Geophysical Society*
- Associate Editor, *Journal of Geophysical Research*
- International Editor, *Earth, Planets and Space*
- Topical Editor, *Geochemistry, Geophysics, Geosystems (G-cubed)* special theme on *Lithosphere-Asthenosphere Boundary*

*S. Lebedev*

- Associate Editor, *Geochemistry, Geophysics, Geosystems (G-cubed)*
- Institutional representative, *Incorporated Research Institutions for Seismology (IRIS)*
- National co-representative, *European Plate Observing System (EPOS)*
- Titular Member (member for Ireland), *European Seismological Commission (ESC)*
- An interview: "How solid is the Earth's crust where tectonic plates collide?" Broadcast on 10th Feb. 2011 on 103.2 Dublin City FM, on 'The Show with an Irish Spin on Science' with Seán Duke.

*Z. Martinec*

- Editor, *International Journal of Geophysics*.

*M.R. Muller*

- Committee Member of Geothermal Association of Ireland (co-opted as International Liaison Officer, 6 July, 2011).

# 16 Productivity

## 16.1 Publications in International Literature

**Agius, M.R.,** and P. Galea (2011), A single-station automated earthquake location system at Wied Dalam Station Malta, *Seismol. Res. Lett., 82(4)*, 545-559, doi: 10.1785/gssrl.82.4.545.

Bartzsch, S., **S. Lebedev**, and T. Meier (2011), Resolving the lithosphere-asthenosphere boundary with seismic Rayleigh waves, *Geophys. J. Int.,* 186, 1152-1164.

Becker, T.W., **S. Lebedev**, and M.D. Long (2011), On the relationship between azimuthal anisotropy from shear wave splitting and surface wave tomography, *J. Geophys. Res.*, accepted November, 2011.

Dostal, J., **Z. Martinec**, and M. Thomas (2012), The modelling of toroidal magnetic field induced by tidal ocean circulation, *Geophys. J. Int.,* in press.

Endrun, B., **S. Lebedev**, T. Meier, **C. Tirel**, and W. Friederich (2011), Complex layered deformation within the Aegean crust and mantle revealed by seismic anisotropy, *Nature Geoscience,* 4, 203-207.

Evans, R.L., **A.G. Jones**, X. Garcia, **M. Muller**, M. Hamilton, S. Evans, S. Fourie, J. Spratt, S. Webb, H. Jelsma, and D. Hutchins (2011), The electrical lithosphere beneath the Kaapvaal Craton, Southern Africa, *J. Geophys. Res. - Solid Earth*, *116*, B04105, doi: 10.1029/2010JB007883, 16pp.

Farquharson, C.G., and **M.P. Miensopust** (2011), Three-dimensional finite-element modelling of magnetotelluric data with a divergence correction, *J. Applied Geophys., 75*, 699 - 705, doi: 10.1016/j.jappgeo.2011.09.025.

**Fullea, J.**, **M.R. Muller,** and **A.G. Jones** (2011), Electrical conductivity of continental lithospheric mantle from integrated geophysical and petrological modelling: Application to the Kaapvaal Craton and Rehoboth Terrane, southern Africa *J. Geophys. Res. – Solid Earth, 116*, B10202, doi: 10.1029/2011JB008544.

Jiménez-Munt, I., M. Fernàndez, J. Vergés, D. Garcia-Castellanos, **J. Fullea**, M. Pérez-Gussinyé, and J.C. Afonso (2011), Decoupled crust-mantle accommodation of Africa-Eurasia convergence in the NW-Moroccan margin, *J. Geophys. Res.*, *116,* B08403, doi: 10.1029/2010JB008105.

**Jones, A.G**. (2011). Three-dimensional galvanic distortion of three-dimensional regional conductivity structures: Comments on "Three-dimensional joint inversion for magnetotelluric resistivity and static shift distributions in complex media" by Y. Sasaki and M.A. Meju (2006). *J. Geophys. Res*., **116**, B12104, doi: 10.1029/2011JB008665.

**Jones, A.G.** (2012), Distortion decomposition of the magnetotelluric impedance tensors from a one-dimensional anisotropic Earth. *Geophys. J. International*, in press, doi: 10.1111/j.1365-246X.2012.05362.x

Klemann, V., and **Z. Martinec** (2011), Contribution of glacial-isostatic adjustment to the geocenter motion, *Tectonophysics, 511*, 99-108, doi: 10.1016/j.tecto.2009.08.031.

Ledo, J., **A.G. Jones**, A. Siniscalchi, J. Campanyà, **D. Kiyan**, G. Romano, M. Rouai, and TopoMed MT Team (2011), Electrical signature of modern and ancient tectonic processes in the crust of the Atlas mountains of Morocco, *Physics of the Earth and Planetary Interiors, 185*, 82-88, doi: 10.1016/j.pepi.2011.01.008.

**Le Pape, F**., **A.G. Jones**, **J. Vozar**, and W. Wei (2011), Crustal weakening and transgressive melt penetrative intrusion in northern Tibet, Nature Geoscience, accepted subject to minor revision.

**Miensopust, M.P.**, and **A.G. Jones** (2011), Artifacts of isotropic inversion applied to anisotropic magnetotelluric data. *Geophys. J. Int., 187*, 677 - 689, doi: 10.1111/j.1365-246X.2011.05157.x.

**Miensopust, M.P., A.G. Jones, M.R. Muller**, X. Garcia, and R.L. Evan (2011), Lithospheric structures and Precambrian terrane boundaries in northeastern Botswana revealed through magnetotelluric profiling as part of the Southern African Magnetotelluric Experiment (SAMTEX). *J. Geophys. Res. - Solid Earth*, *116*, B02401, doi:10.1029/2010JB007740.

O'Donnell, J.P., E. Daly, C. Tiberi, I.D. Bastow, **B.M. O'Reilly, P.W. Readman,** and **F. Hauser** (2011), Lithosphere-asthenosphere interaction beneath Ireland from joint inversion of teleseismic P-wave delay times and GRACE gravity, *Geophys. J. Int., 184*, 1379-1396, doi: 10.1111/j.1365-246X2011.04921.x.

**Polat, G., S. Lebedev, P.W. Readman, B.M. O'Reilly,** and **F. Hauser** (2011), Anisotropic Rayleigh-wave tomography of Ireland's crust: Implications for

crustal accretion and evolution within the Caledonian Orogen, *Geophys. Res. Lett*., **39**, L04302, doi: 10.1029/2012GL051014.

Rogozhina, I., **Z. Martinec**, J.M. Hagedoorn, M. Thomas, and K. Fleming, (2011), On the long-term memory of the Greenland Ice Sheet, *J. Geophys. Res., 116*, F01011, doi: 10.1029/2010JF001787.

**Roux, E**., M. Moorkamp, **A.G. Jones**, M. Bischoff, B. Endrun, **S. Lebedev,** and T. Meier (2011), Joint inversion of long-period magnetotelluric data and surface-wave dispersion curves for anisotropic structure: Application to data from Central Germany, *Geophys. Res. Lett.,* 38, L05304, doi: 10.1029/2010GL046358.

Sacchetti, F., S. Benetti, A. Georgiopoulou, P.M. Shannon, **B.M. O'Reilly**, P. Dunlop, R. Quinn, and C.Ó Cofaigh (2011), Deep water geomorphology of the formerly glaciated Irish margin from high-resolution marine geophysical data, *Marine Geology*, **291-294**, 113-131.

Souček, O., and **Z. Martinec** (2011), ISMIP-HEINO experiment revised: effect of higher-order approximation and sensitivity study, *J. Glaciol., 57*, 1158-1170.

Souček, O., **Z. Martinec**, and J. Velímský (2011), Vector potential formulation of a quasi-static EM induction problem: existence, uniqueness and stability of the weak solution, *Int. J. Geomath., 2*, 265-279, doi: 10.1007/s13137-011-0019-9.

Spada, G., V.R., Barletta, V. Klemann, R.E.M. Riva, **Z. Martinec**, P. Gasperini, B. Lund, D. Wolf, L.L.A. Vermeersen, and M. King (2011), A benchmark study for glacial isostatic adjustment codes, *Geophys. J. Int., 185*, 106-132, doi: 10.1111/j.1365-246X.2011.04952.x.

Tanaka, Y., V. Klemann, **Z. Martinec**, and R.E.M. Riva (2011), Spectral-finite element approach to viscoelastic relaxation in a spherical compressible Earth: application to GIA modelling, *Geophys. J. Int., 184*, 220--234, doi: 10.1111/j.1365-246X.2010.04854.x.

### 16.1.1 Submissions to International Literature

**Jones, A.G., D. Kiyan**, and the TopoMed MT team (2011), Comment on "Deep resistivity cross section of the intraplate Atlas Mountains (NW Africa): New evidence of anomalous mantle and related Quaternary volcanism" by Anahnah et al. (2011), submitted to *Tectonics*.

**O'Reilly, B.M**., **F. Hauser**, and **P.W. Readman** (2011), The fine-scale seismic structure of the upper lithosphere within accreted Caledonian lithosphere: implications for the origins of the "Newer Granites", submitted to *J. Geol. Soc*., London.

Welford, K.J., P. M. Shannon, **B. M. O'Reilly**, and J. Hall (2011), Comparison of lithospheric density and Moho structure variations across the Orphan Basin/Flemish Cap and Irish Atlantic conjugate continental margins from constrained 3-D gravity inversions,sSubmitted to *J. Geol. Soc.*, London.

## 16.2 Unpublished Reports

**Muller, M.R., A.G. Jones,** and **C. Hogg** (2011), 1-D Modelling of MT Site Responses (Report 3), Report submitted to Gaelectric, 5 March, 2011.

**Muller, M.R., A.G. Jones, S. Sihelnik,** and **C. Hogg** (2011), 2-D Magnetotelluric and Gravity Modelling (Final Report - Report 4), Report submitted to Gaelectric, 22 December, 2011.

## 16.3 Theses

**Ayres, L.A.** (2011), Constraints from magnetotellurics on the subsurface structure and emplacement of the Mourne Granites. M.Sci. degree awarded June, 2011. Supervisor: **M.R. Muller**, co-supervisor: C. Stevenson, University of Birmingham, UK.

**Loewer, M.** (2011), Investigation of the geothermal energy potential of the Lough Neagh Basin, Northern Ireland, using magnetotelluric and gravity modelling, M.Sc. degree awarded 2 September, 2011. Supervisor: **M.R. Muller**, co-supervisor: T. Kalscheuer, Swiss Federal Institute of Technology Zurich, Switzerland.

**Sihelnik, S.** (2011), Investigation of compressed air energy storage potential in the Larne Basin, Northern Ireland, using magnetotelluric and gravity methods. M.Sc. degree awarded 2 September, 2011. Supervisor: **M.R. Muller**, co-supervisor: T. Kalscheuer, Swiss Federal Institute of Technology Zurich, Switzerland.

**Schmoldt, J.-P.** (2011), Multidimensional isotropic and anisotropic investigation of the Tajo Basin subsurface A novel anisotropic inversion approach for subsurface cases with oblique geoelectric strike directions. Ph.D. degree awarded November, 2011. Supervisor: **A.G. Jones**.

**Vannes, N.** (2011), Terrain corrections in gravimetry and gradiometry for GRACE and GOCE satellite missions. M.Sci. degree awarded June, 2011. Supervisor: **Z. Martinec**.

**Yeomans, C.** (2011), Geothermal implications of the Mourne Mountains: constraints from magnetotelluric modeling. M.Sci. degree awarded June, 2011. Supervisor: **M.R. Muller**, co-supervisor: C. Stevenson, University of Birmingham, UK.

## 16.4 Invited presentations

**Agius, M.R**., and **S. Lebedev** (2011), The crustal and mantle structure beneath Tibet, from shear-velocity profiles, Invited seminar, University of Malta, 4 March.

**Blake, T.** (2011), The Irish National Seismic Network (INSN) - New developments and directions, TCD Lunchtime Seminars, Dublin, Ireland, 28 January.

**Blake, T.** (2011), The Irish National Seismic Network (INSN) - A Wave of Scientific Opportunity, ADLEC Conference, Limerick, Ireland, 10 November.

**Fullea, J.** (2011), Integrated geophysical-petrological modelling of surface-wave, topography, surface heat flow and xenoliths data: application to Central Mongolia's lithosphere, 4th Workshop of TopoScandiaDeep, NGU, Trondheim, Norway, July 2011.

**Fullea, J.** (2011), Integrated geophysical and petrological modelling: central Mongolia and the Kaapvaal craton, Research Seminar, Univ. Leicester, UK, November 2011.

**Fullea, J.** (2011), Electrical conductivity of continental lithospheric mantle from an integrated geophysical and petrological approach: application to the Kaapvaal Craton, southern Africa, AGU Fall Meeting, DI34B-02, San Francisco, USA, December 2011.

**Jones, A.G.** (2011), Mapping the electrical lithosphere-asthenosphere boundary (eLAB) and its correspondence with seismic (sLAB) and petrological (pLAB) LABs, Earthscope Workshop on the Lithosphere Asthenosphere Boundary, 19-21 September, Portland, Oregon, USA.

**Jones, A.G**., **J. Vozar**, **F. Le Pape**, W. Wei, S. Jin, G. Ye, D. Hao, M.J. Unsworth, and the INDEPTH MT Team (2011), Constraints on Processes from the

Electrical Conductivity of the Tibetan Plateau Lithosphere, INDEPTH Workshop, Beijing, China, 15 November.

**Jones, A.G**., 2011. Combined seismological and electromagnetic studies of the lithosphere of Southern Africa. **Keynote presentation**, The International Symposium on Deep Exploration into the Lithosphere, Beijing, China, 16-18 November.

**Jones, A.G**. (2011), Joint inversion of seismic and electromagnetic data for lithospheric parameters, The International Symposium on Deep Exploration into the Lithosphere, Beijing, China, 16-18 November.

**Jones**, **A.G., M.R. Muller**, J.S. Daly, A. Allen, R. Goodman, N.H. Hunter Williams, M. Lee, D. Reay, M. Feely, P. Hanly, and R. Pasquali (2011), Harnessing Earth's heat for energy in Ireland: the IRETHERM project, IGA Lecture, TCD, Dublin, Ireland, 19 October and UCC, Cork, Ireland, 20 October.

**Jones, A.G., D.T. Khoza, M.R. Muller**, R.L. Evans, M.P. Hamilton, **M.P. Miensopust**, X. Garcia, P. Cole, T. Ngwisanyi, D. Hutchins, W. Pettit, H. Jelsma, T. Aravanis, C.J.S. Fourie, S. Webb, J. Wasborg, and The SAMTEX Team (2011), Lithospheric geometries revealed through electromagnetic imaging: SAMTEX (Southern Africa MagnetoTelluric Experiment) observations and results, AGU FallMeeting, San Francisco, California, USA, 5-9 December.

**Lebedev, S**. (2011), Seismic imaging of lithospheric structure and deformation in Europe and other continents, Seminar, University of Potsdam, Germany, 2 May.

**Lebedev, S**. (2011), Lithospheric structure and deformation, Seminar, University of Kiel, Germany, 4 May.

**Lebedev, S.** (2011), Seismic tomography: Imaging the structure and dynamics of the Earth, Seminar, DCU, School of Physical Sciences, Dublin, Ireland, 27 October.

**Muller, M.R.**, **A.G. Jones**, J.S. Daly, A. Allen, R. Goodman, N.H. Hunter Williams, M. Lee, D. Reay, M. Feely, P. Hanly, and R. Pasquali (2011), IRETHERM: Innovation within a new research project to explore and assess Ireland's deep, low-enthalpy geothermal energy potential, Global Geothermal Energy Summit, Reykjavik, Iceland, 12-13 October.

Réalteolaíocht 7 Réaltfiric

# Astronomy and Astrophysics Research Report 2011

Presented to the Governing Board
of the School of Cosmic Physics
on 26 March 2012.

## Contents

# 1 Research Reports

## 1.1 High-Energy Astrophysics

### 1.1.1 Final results from the Ultra-Heavy Cosmic Ray Experiment on the Long Duration Exposure Facility

*J. Donnelly (DIT), A. Thompson, D. O'Sullivan, J. Daly, L. Drury, V. Domingo (U. Valencia) and K.-P. Wenzel (ESTEC)*

The LDEF Ultra-Heavy Cosmic-Ray Experiment (UHCRE) detected Galactic cosmic rays (GCRs) of charge $Z \geq 70$ in Earth orbit with an exposure factor of $170\,\mathrm{m}^2\,\mathrm{sr\,yr}$, much larger than any other experiment. A careful re-analysis was made of the final data from the experiment using modern techniques of Monte-Carlo likelihood estimation. The major results include the first statistically significant uniform sample of GCR actinides with 35 events passing quality cuts, evidence for the existence of transuranic nuclei in the GCR with one $_{96}$Cm candidate event, and a low $_{82}$Pb/$_{78}$Pt ratio consistent with other experiments. The probability of the existence of a transuranic component is estimated as 96%, while the most likely $_{92}$U/$_{90}$Th ratio is found to be 0.4 within a wide 70% confidence interval ranging from 0 to 0.96 (see Figure 1). Overall, the results are consistent with a volatility-based acceleration bias and source material which is mainly ordinary interstellar medium material with some recent contamination by freshly synthesised material. Uncertainty in the key $_{92}$U/$_{90}$Th ratio is dominated by statistical errors resulting from the small sample size and any improved determination will thus require an experiment with a substantially larger exposure factor than the UHCRE.

The paper was accepted for publication in the ApJ in early 2012.

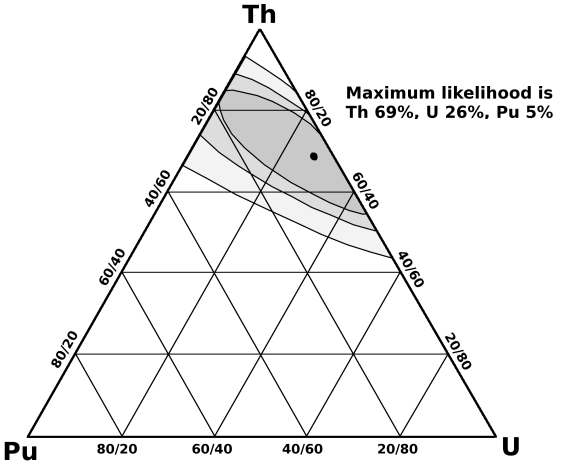



Figure 1: Likelihood contours (at the 90%, 70% and 50% levels) for a ternary U/Th/Pu composition of the actinides in the GCR as derived from the UHCRE data.

### 1.1.2 Nuclear reactions in hot astrophysical plasmas

*F. Aharonian, and E. Kafexhiu (MPIK, Heidelberg, Germani), G. Vila (IAR, Buenos-Aires, Argentina)*

Low-density optically thin two-temperature ($T_\mathrm{i} \gg T_\mathrm{e}$) plasmas with ion temperature $T_\mathrm{i}$ exceeding $10^{10}$K, can form near compact relativistic objects, such as accretion flows close to black holes and strong shock waves related, for example, to supernova explosions. The importance of nuclear reactions in such plasmas, including the excitation and spallation of nuclei, production of neutrons and their capture by protons, proton-neutron bremsstrahlung, etc., has been recognized in the early 1980s. However, the lack of comprehensive data banks of relevant nuclear reactions and the limited computational power did not allow detailed theoretical studies. Recent developments in these areas make it timely to conduct comprehensive studies which are of great interest, in particular in the context of scientific programs of future low-energy cosmic $\gamma$-ray spectrometry. Recently, the publicly available code TALYS, we have built a large nuclear network relevant for temperatures exceeding $10^{10}$ K. We have studied the evolution of the chemical composition and accompanying prompt gamma-ray emission of such high temperature plasmas. In particular, the abundances of light elements D, T, $^3$He, $^4$He, $^6$Li, $^7$Li $^9$Be, $^{10}$B, $^{11}$B have been calculated, and the implications

on these results have been discussed.

### 1.1.3 Origin of the extremely hard VHE gamma-ray spectra of blazers

*F. Aharonian, E. Lefa, F. Rieger and O. Zacharopoulou (MPIK, Heidelberg, Germany), D. Khangulyan (ISAS/JAXA, Tokyo, Japan), L. Costamante (Stanford University, USA)*

The very high energy (VHE) gamma-ray spectra of some TeV blazars, after being corrected for absorption due to interactions with the extragalactic background light (EBL), appear unusually hard. This poses challenges to conventional acceleration and emission models. We have proposed and developed two different scenarios of formation of hard spectra of blazers. The first one is based on the assumption of internal time-dependent absorption of gamma-rays inside the source. In particular, we have studied this possibility for gamma-rays produced through synchrotron radiation of ultrarelativistic protons in highly magnetized blobs to two blazers - 1ES 0229+200 and 3C 66A, and have shown that for certain combinations of reasonable model parameters, even with quite modest energy requirements, the scenario allows a self-consistent explanation of the non-thermal emission of these objects in the keV, GeV, and TeV energy bands. The second model is based on the assumption of production of gamma-rays by electrons with very hard acceleration spectrum. We have investigated the parameter space that allows the production of hard TeV gamma-ray spectra within time-dependent leptonic models, both for synchrotron self-Compton and external Compton scenarios. In the context of the interpretation of very hard gamma-ray spectra, time-dependent considerations become crucial because even extremely hard, initial electron distributions can be significantly deformed due to radiative energy losses. We show that very steep VHE spectra can be avoided if adiabatic losses are taken into account. Another way to keep extremely hard electron distributions in the presence of radiative losses is to assume stochastic acceleration models that naturally lead to steady-state, relativistic, Maxwellian-type particle distributions. We demonstrated that in either case leptonic models can reproduce TeV spectra as hard as $dN/dE \propto E^{-1}$. In the case of very hard spectra of the blazer Mkn 501 reported by the *Fermi* collaboration during the high state of the source in 2009, we have introduce a "leading blob" scenario, applicable to active flaring episodes, when one (or a few) of these components become distinct over the "background" emission, producing hard spectral features.

### 1.1.4 Fermi Bubbles: Giant, Multibillion-Year-Old Reservoirs of Galactic Center Cosmic Rays

*F. Aharonian and R. Crocker (MPIK, Heidelberg, Germany)*

Recently evidence has emerged for enormous features in the gamma-ray sky reported by the *Fermi* collaboration: bilateral âĂİbubblesâĂİ of emission centered on the core of the Galaxy and extending to around ±10 kpc from the Galactic plane. These structures are coincident with a nonthermal microwave âĂİhazeâĂİ and an extended region of X-ray emission. The bubblesâĂŹ gamma-ray emission is characterized by a hard and relatively uniform spectrum and uniform surface intensity, and an overall luminosity $4 \times 10^{37}$ erg/s, around 1 order of magnitude larger than their microwave luminosity while more than order of magnitude less than their X-ray luminosity. Here we show that the bubbles are naturally explained as due to a population of relic cosmic-ray protons and heavier ions injected by processes associated with extremely long time scale ($\geq 8$ Gyr) and high star formation rate in the Galactic center. If the model is correct, the planned KM3NeT high energy neutrino detector should be able to detect neutrino signal from Fermi Bubbles.

### 1.1.5 Radioactivity and electron acceleration in supernova remnants

*F. Aharonian and V. Zirakashvili (IZMIRAN, Troitsk, Russia)*

We argue that the decays of radioactive nuclei related to $Ti^{44}$ and $Ni^{56}$ ejected during supernova explosions can provide a vast pool of mildly relativistic positrons and electrons which are further accelerated to ultrarelativistic energies by reverse and forward shocks. This interesting link between two independent processesâĂŤthe radioactivity and the particle accelerationâĂŤcan be a clue for solution of the well known theoretical problem of electron injection in supernova remnants. In the case of the brightest radio source Cas A, we demonstrate that the radioactivity can supply adequate number of energetic electrons and positrons for interpretation of observational data, provided a modest preacceleration (presumably of stochastic origin) to energies $E_{\rm inj} \sim 0.1$ GeV takes place in the upstream regions of the forward and reverse shocks. The proposed scenario can explain not only the overall flux of galactic CR electrons by SNRs, but also the recently reported tendency of gradual increase of the positron-to-electron ratio with energy.

### 1.1.6 X-Ray diagnostics of giant molecular clouds in the Galactic Center region and past activity of Sgr A*

*F. Aharonian, and H. Odaka, S. Watanabe, Y. Tanaka, D. Khangulyan, T. Takahashi (ISAS/JAXA, Tokyo, Japan)*

Strong iron fluorescence at 6.4 keV and hard-X-ray emissions from giant molecular clouds in the Galactic Center region have been interpreted as reflections of a past outburst of the Sgr A* supermassive black hole. Careful treatment of multiple interactions of photons in a complex geometry is essential for modeling of the reprocessed emissions from the dense clouds. We have developed a new numerical model for calculations of the process of X-ray reflection from molecular clouds based on Monte Carlo simulations, and present the first calculations of morphological and spectral properties of the reflected X-ray emission for different configurations of Sgr B2, the most massive molecular cloud in our Galaxy. The morphology of scattered hard X-rays above 20 keV is significantly different from that of iron fluorescence due to their large penetrating power into dense regions of the cloud, probing the structure of the cloud. High-resolution spectra provide quantitative evaluation of the iron line and its Compton shoulder to constrain the mass and the chemical composition of the cloud. These predictions can be checked in the near future with future X-ray missions such as NuStar (hard X-rays) and ASTRO-H (both iron lines and hard X-rays).

### 1.1.7 Non-variable cosmologically distant gamma-ray emitters as a propagation imprint of ultra-high-energy protons

*F. Aharonian, and A. Prosekin, S. Kelner (MPIK, Heidelberg, Germany)*

The acceleration sites of ultra-high-energy (UHE) protons can be traced by the footprint left by these particles when they propagate through cosmic microwave background radiation (CMBR). Secondary electrons produced in the extended region of several tens of Mpc are cooled via synchrotron radiation predominantly in the initial direction of the parent protons. This forms a non-variable and compact (almost point-like) source of high-energy gamma rays. The importance of this effect is increased for cosmologically distant objects. Because of severe energy losses, UHE protons cannot reach us even in the case of extremely weak intergalactic magnetic fields. Moreover, at high redshifts the energy conversion from protons to secondary particles becomes significantly more effective because of the denser and more energetic CMB in the past. This increases the chances of UHE cosmic rays to be traced by the secondary synchrotron gamma radiation. We discuss the energy budget and the redshift dependence of the energy transfer efficiency from UHE protons to synchrotron radiation. The angular and spectral distributions of radiation in the gamma- and X-ray energy bands are calculated and discussed in the context of their detectability by the *Fermi* gamma-ray and *Chandra* X-ray observatories.

### 1.1.8 A local source of ultrahigh-energy cosmic-ray nuclei?

*F. Aharonian, and A. Taylor (ISDC, Versoix, Switzerland), M. Ahlers (Stony Brook, New York)*

Recent results of the Pierre Auger Cosmic Ray Observatory fluorescence detectors indicate an increasingly heavy composition of ultra-high energy (UHE) cosmic rays. Assuming that this trend continues up to the highest energies observed by the Auger surface detectors, we obtained robust constraints on the local source distribution of UHE cosmic ray nuclei. Utilizing an analytic description of UHE CR propagation, we derived the expected spectra and composition for a wide range of source emission spectra. We found that sources of intermediate-to-heavy nuclei are consistent with the observed spectra and composition data above the ankle. This consistency requires the presence of nearby sources within 60 Mpc and 80 Mpc for silicon and iron-only sources, respectively. The necessity of these local sources becomes even more compelling in the presence of nano-Gauss local extragalactic magnetic fields.

### 1.1.9 Constraining the emissivity of ultrahigh energy cosmic rays in the distant universe with the diffuse gamma-ray emission

*F. Aharonian, Xiang-Yu Wang; Ruo-Yu Liu (Nanjing University, China)*

Ultrahigh cosmic rays (UHECRs) with energies exceeding $10^{19}$eV emitted at cosmological distances are attenuated by cosmic microwave radiation (CMBR) through photomeson processes. Lower energy extragalactic cosmic rays can only travel a linear distance smaller than 1 Gpc in the Hubble time due to the diffusion if the extragalactic magnetic fields are as strong as nano-Gauss. These prevent us from directly observing most of the UHECRs in the universe, and thus the observed UHECR intensity reflects only the emissivity in the nearby universe within hundreds of Mpc. However, UHECRs in the distant universe, through interactions with CMBR, produce electrons and gamma rays that in turn initiate electromagnetic cascades. The secondary cascade radiation forms part of the extragalactic diffuse GeV-TeV gamma-ray radiation and, unlike the original UHECRs, is observable. Motivated by new measurements of extragalactic diffuse gamma-ray background radiation by Fermi/Large Area Telescope, we obtained upper limit placed on the UHECR emissivity in the distant universe by requiring that the cascade radiation they produce not exceed the observed levels. By comparison with the gamma-ray emissivity of candidate UHECR sources, e.g. gamma-ray bursts (GRBs) and active galactic nuclei (AGN) at high redshifts, we find that the obtained upper limit for a flat proton spectrum is 30 times larger than the gamma-ray emissivity in GRBs and approximately 10 times smaller than the gamma-ray emissivity in BL Lac objects. In the case of iron nuclei composition, the derived upper limit of UHECR emissivity is a factor of 3-5 times higher. Robust upper limit on the cosmogenic neutrino flux is also obtained, which is marginally reachable by the IceCube detector and the next-generation detector UHECR detector JEM-EUSO.

### 1.1.10 Non-thermal processes in relativistic outflows

*V. Bosch-Ramon, F. A. Aharonian*

Astrophysical sources with relativistic outflows are powerful non-thermal emitters from radio to gamma rays. These relativistic outflows interact with their environment in galactic and extragalactic objects, leading to complex magnetohydrodynamical processes, particle acceleration and non-thermal emission. Usually, leptonic mechanisms are good candidates for the non-thermal emission of these sources, with synchrotron radiation dominating from radio to X-rays, and inverse Compton in gamma rays (e.g. [86, 58, 27, 24]). The properties of the non-thermal emission are strongly linked to dynamical processes of the involved flows (e.g. [23, 25]), and thus non-radiative losses are to be considered together with radiative ones (e.g. [86]). Al-

though less common, thermal radiation can be also expected in these sources (e.g. binary systems with strong stellar winds, or in large-scale interactions with the external material), its study being also a source of physical information [85, 24]. Radiation reprocessing in some cases (e.g. compact binary systems, base of jets) is to be accounted for, and gamma-ray absorption and creation of pairs, with their subsequent emission, can be of primary importance [26, 87].

### 1.1.11 Multiwavelength emission from the gamma-ray loud binary systems.

*M. Chernyakova, A. Neronov (ISDC, Geneva)*

Gamma-ray-loud binary systems (GRLB) are a newly identified class of X-ray binaries in which either accretion onto the compact object (a neutron star, or a black hole), or interaction of an outflow from the compact object with the wind and radiation emitted by the massive companion star leads to the production of very-high energy (VHE) gamma-ray emission. Four such systems PSR B1259-63, LS 5039, LSI +61Âś 303 and HESS J0632+057, have been firmly detected as persistent or regularly variable TeV gamma-ray emitters.

PSR B1259-63 is the only GRLB where we know the nature of the compact object - in this system 47.76 ms radio pulsar is orbiting a massive star (LS 2883) in a highly elliptical (e 0.87) orbit with a period of about 3.4 years. Shock interaction between the relativistic pulsar wind and the wind and photon field of the Be star is believed to give rise to the variable unpulsed X-ray emission observed throughout the orbit and the unpulsed radio and TeV $\gamma$-rays observed within a few months of periastron. The energy of the relativistic particles of the pulsar wind is still not known for sure and there was a hope that Fermi observations of the system will finally help to resolve this issue. In order to prepare for the December 2010 periastron passage we have organized along with Fermi team a multiwavelength (from radio up to VHE) campaign [1]. While the periastron passage itself doesn't bring too big surprises, the huge post-periastron flare observed only at GeV energy was absolutely unexpected. An interesting theoretical explanation of the phenomena was proposed in [23, 58], but the work on better understanding of the physical processes taking place in the system is still ongoing.

LSI +61 303 is another high-mass X-ray binary which emits high-energy (GeV-TeV) gamma-rays. It is known to be variable on different timescales. The orbital period is 26.5 days (Gregory 2002), the superorbital period is about 1667 days. In LSI +61 303, the high-energy particle outflow is directly observed in the radio band, where angular resolution is sufficient to resolve the source and detect variations of its morphology on the orbital period timescale. The observed morphological changes indicate that the outflow is, most probably, not a jet with a well-defined position angle on the sky, but is rather a variable morphology outflow filling a region the size 100 - 1000 times larger than the binary separation distance. The radio signal could not be used to trace the outflow down to the production site inside the binary orbit because of the free-free absorption in the dense stellar wind environment. To understand the nature of the high energy particle carrying outflow one has to use complementary high-energy data in X-ray and/or gamma-ray bands. In the X-ray band the source is known to exhibit one flare per orbit, on average preceding the radio one. The GeV band light curve during the first year of LAT observations also exhibited a one-flare pattern. Both X-ray and GeV band light curves exhibit large orbit-to-orbit variations so that the systematic periodic variability is often washed out by an erratic behavior of the source. The origin of the X-ray and radio flares as well as the relation between the flaring activity of the source in different energy bands is not well understood. The orbital phase of the periodic flares drifts on a superorbital timescale by half-an-orbit. Such a drift is difficult to explain in scenarios based on various types of precession, where one expects a drift by a full orbit. An alternative possibility for the explanation of the 4.5 yr timescale is the buildup and decay of the equatorial disk around the massive Be star in the system. A new insight into the nature of the 4.5 yr period-

icity/variability might be given by the study of the changes in the behavior of the X-ray and gamma-ray emission on this timescale. We performed such a study based on the analysis of the monitoring of the source with RXTE, INTEGRAL, and Fermi. The X-ray/gamma-ray data were complemented by the contemporaneous radio monitoring data. In our work we discover a systematic constant time lag between the X-ray and radio flares, persistent over a long, multi-year, timescale (see Fig. 2). We propose that the constant phase lag corresponds to the time of flight of the high-energy particle-filled plasma blobs from inside the binary to the radio emission region at the distance 10 times the binary separation distance. We put forward a hypothesis that the X-ray bursts correspond to the moments of formation of plasma blobs inside the binary system. Paper on this study was accepted to ApJL in early 2012.

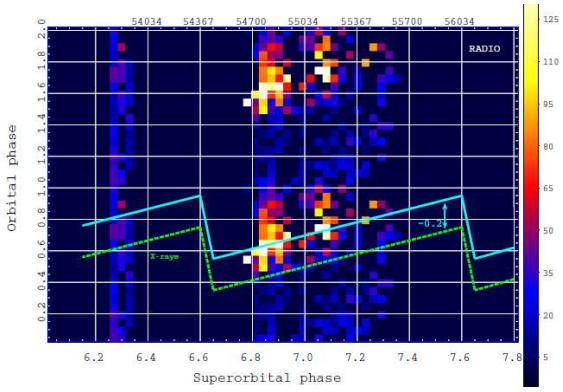



Figure 2: Radio flux from LSI +61 303 as a function of the orbital and superorbital phases. Green and cyan lines allow comparison of X-ray and radio superorbital variability patterns.

### 1.1.12 Systematic study of the variable GeV sky.

*M.Chernyakova, D.Malyshev(BITP, Kiev)*

The study of the sky using the most energetic photons Ãś gamma-ray astronomy - plays a crucial role in detecting and exploring high-energy phenomena in the universe. The observation of the sky with the recently launched FERMI mission opened a completely new window in gamma-ray astronomy and reveals more than 1500 point-like gamma-ray sources candidates. Some of these sources demonstrate surprisingly high efficiency of particle acceleration, close to theoretical limits. The studying of the gamma-ray properties (spectral and timing characteristics) of extreme accelerators is required for the testing theoretical models of particle acceleration and understanding the nature of the source. However, the detection of gamma-ray sources, especially at low Galactic latitudes (where the sources most probably have galactic origin that is an interesting sub-class of extreme accelerators) is a complicate task. Strong diffuse emission from the Galaxy prevents reliable identification of isolated point sources. Indeed, typical angular scale of spatial variations of diffuse gamma-ray emission is comparable or smaller than the point spread function of FERMI/LAT, especially at the low energy (100MeV) end of the LAT energy range. This means that spatial variations of intensity of diffuse gamma-ray emission could be easily miss-interpreted as possible new unidentified point sources. To distinguish the diffuse emission excesses from real sources, one should manage to use certain properties of real sources (e.g. pulsars, supernova remnants or binary systems) which could not be found in the excesses of diffuse emission. The most straightforward distinguishing property of real gamma-ray sources is variability. Diffuse gamma-ray emission, both Galactic and Extragalactic is not expected to be variable on week / month / year time scales. To the contrary, compact gamma-ray sources, such as gamma-ray loud binaries, are generically expected to be variable on the orbital time scale. Neutron star and stellar mass black hole powered sources could be variable on the time scale as short at the light crossing time of the compact object, which is in the millisecond range. A simple way to verify if gamma-ray emission from a given direction on the sky is variable or constant is to analyze the light curve and check if it is consistent with a constant flux. In order to check this idea we built a set of variability maps at different energies and on different timescales (see e.g. Fig.3) have been built using all available for the moment Fermi data (3years). These maps reveal a number of variable sources, some of which are

unidentified sources from the second FERMI catalog and some of them are not presented in 2 year catalog. Now we are looking in more details into each particular case. The work is ongoing.

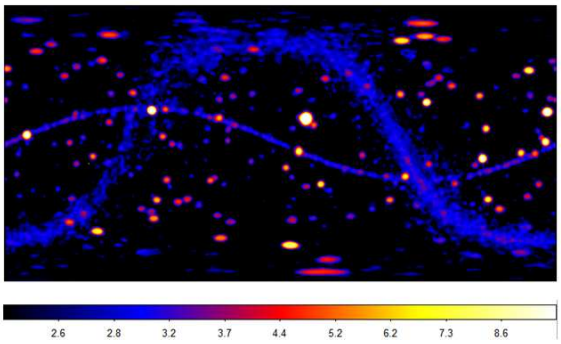



Figure 3: Variability map of the sky at energies 300MeVÃş300GeV on 6 hours timescale

#### 1.1.13 Strong outbursts activity of the X-ray pulsar X Persei in 2001-2011

*M.Chernyakova, A. Lutovinov, S. Tsygankov (IKI, Moscow)*

We present a comprehensive analysis of the X-ray pulsar X Persei over the period 1996 to 2011, encompassing the quite low state and subsequent strong outbursts activity. Using data from the *RXTE* and *Swift* observatories we detected several consecutive outbursts, in which the source luminosity was increased by factor of $\sim 5$ up to $L_X \simeq 1.2 \times 10^{35}$ ergs. This is only the second episode from the X Persei discovery, when the source is observed in a high state. The source spectrum in a standard energy band $(4-25$ keV) is remained a relatively stable with flux changes and can be well described by two models, including both thermal and non-thermal components. Data of the *INTEGRAL* observatory allowed us to register at the high significance level the cyclotron absorption line in the source spectrum and, for the first time, to significantly detect a hard X-ray emission from the pulsar up to $\sim 160$ keV. We report also drastic changes of the pulsar pulse period during the period of the outbursts activity: a long period of the spin-down was changed by the spin-up with the rate of $\dot{P}/P \simeq -(3-5)\times 10^{-3}$ yr$^{-1}$, that by several times higher than previous rates of spin-up and spin-down. No significant correlation between optical and X-ray fluxes at any time lag from dozens of days to years was found. Paper on this study is submitted to MNRAS.

#### 1.1.14 Study of extragalactic soft X-ray transients in M31

*N. Nooraee, P. Callanan (UCC)*

During numerous X-ray observations of M31 over the last decade, more than 50 soft X-ray transients have been detected. Galactic soft X-ray transients, a subgroup of low mass X-ray binaries, show evidence for being powered by accreting stellar mass black holes. To confirm the presence of black holes in soft X-ray transients, high resolution optical observations are needed which the Hubble Space Telescope is able to provide. In this study several new transients were detected and investigated with follow up optical observations. The study of the light curves of bright soft X-ray transients, from outburst down to quiescence, may help to understand the physical mechanisms responsible for the outburst, in particular whether disk irradiation can explain the longer outbursts as compared to dwarf novae.

### 1.2 Star Formation

#### 1.2.1 POISSOIN Project: YSO optical NIR spectral survey star forming regions

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Characterising stellar and circumstellar properties of embedded young stellar objects (YSOs) is mandatory for understanding the early stages of the stellar evolution. This task requires the combination of both spectroscopy and photometry, covering the widest possible wavelength range, to disentangle the various protostellar components and activities. At this aim we started the POISSON project (Protostellar

Optical-Infrared Spectral Survey On NTT), a low-resolution optical-near IR spectroscopic survey (0.6âĂŽÃĎÃň2.4 $\mu$m) of a sample of Class I and Class II young stellar objects in six different star forming regions (Chamaeleon I and II, L 1641, Lupus, Vela, and Serpens). The main results of the first two published papers, on Chamaeleon I and II, L 1641 regions, are the following. Low mass YSO empirical classification relies on the shape of the Spectral Energy Distribution (SED) alone. On the basis of the derived stellar properties of our targtes, we show that geometrical effects can significantly modify the SED shapes, and sometimes the classical YSO classification does not match with the real age of the objects. The youngest YSOs have the highest $\dot{M}_{acc}$, whereas the oldest YSOs do not show any detectable jet activity in either images and spectra. We also observe a clear correlation among the YSO $\dot{M}_{acc}$, $M_*$, and age. For YSOs with $t > 10^5$ yr and $0.4\,M_\odot \leq M_* \leq 1.2\,M_\odot$, a relationship between $\dot{M}_{acc}$ and $t$ ($\dot{M}_{acc} \propto t^{-1.2}$) has been inferred, consistent with mass accretion evolution in viscous disc models and indicating that the mass accretion decay is slower than previously assumed. Finally, our results suggest that episodic outbursts are required for Class I YSOs to reach typical classical T Tauri stars stellar masses.

### 1.2.2 The nature of the embedded intermediate-mass T Tauri star DK Cha

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Most of our knowledge about star formation is based on studies of low-mass stars, whereas very little is known about the properties of the circumstellar material around young and embedded intermediate-mass T Tauri stars (IMTTSs) mostly because they are rare, typically more distant than their lower mass counterparts, and their nearby circumstellar surroundings are usually hidden from us. We present an analysis of the excitation and accretion properties of the young IMTTS DK Cha. The nearly face-on configuration of this source allows us to have direct access to the star-disk system through the excavated envelope and outflow cavity. Based on low-resolution optical and infrared spectroscopy obtained with SofI and EFOSC2 on the NTT we derive the spectrum of DK Cha from ~0.6 $\mu$m to ~2.5 $\mu$m. From the detected lines we probe the conditions of the gas that emits the H I IR emission lines and obtain insights into the origin of the other permitted emission lines. In addition, we derive the mass accretion rate ($\dot{M}_{acc}$) from the relationships that connect the luminosity of the Br$\gamma$ and Pa$\beta$ lines with the accretion luminosity ($L_{acc}$). The observed optical/IR spectrum is extremely rich in forbidden and permitted atomic and molecular emission lines, which makes this source similar to very active low-mass T Tauri stars. Some of the permitted emission lines are identified as being excited by fluorescence. We derive Brackett decrements and compare them with different excitation mechanisms. The Pa$\beta$/Br$\gamma$ ratio is consistent with optically thick emission in LTE at a temperature of ~3500 K, originated from a compact region of ~5 $R_\odot$ in size: but the line opacity decreases in the Br lines for high quantum numbers nup. A good fit to the data is obtained assuming an expanding gas in LTE, with an electron density at the wind base of $\sim 10^{13}$ cm$^{-3}$. In addition, we find that the observed Brackett ratios are very similar to those reported in previous studies of low-mass CTTSs and Class I sources, indicating that these ratios are not dependent on masses and ages. Finally, $L_{acc}$ ~9 $L_\odot$ and $\dot{M}_{acc}$ $\sim 10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$ values were found. When comparing the derived ÂůĬĂĂĎacc value with that found in Class I and IMTTSs of roughly the same mass, we found that ÂůĬĂĂĎacc in DK Cha is lower than that found in Class I sources but higher than that found in IMTTSs. This agrees with DK Cha being in an evolutionary transition phase between a Class I and II source.

### 1.2.3 The outburst of an embedded low-mass YSO in L1641

*A. Caratti o Garatti, R. Garcia Lopez, A. Scholz, T. Giannini (INAF-OAR), J. Eislöffel (TLS), B. Nisini*

*(INAF-OAR), F. Massi (INAF-OAA), S. Antoniucci (INAF-OAR)*

Strong outbursts in very young and embedded protostars are rare and not yet fully understood. They are believed to originate from an increase in the mass accretion rate ($\dot{M}_{acc}$) onto the source. We report the discovery of a strong outburst in a low-mass embedded young stellar object (YSO), namely $2MASS-J05424848-0816347$ or $[CTF93]216-2$, as well as its photometric and spectroscopic follow-up. Using near- to mid-IR photometry and NIR low-resolution spectroscopy, we monitor the outburst, deriving its magnitude, duration, as well as the enhanced accretion luminosity and mass accretion rate. $[CTF93]216-2$ increased in brightness by ~4.6, 4.0, 3.8, and 1.9 mag in the $J$, $H$, $K_s$ bands and at 24 $\mu$m, respectively, corresponding to an $L_{bol}$ increase of ~20 $L_\odot$. Its early spectrum, probably taken soon after the outburst, displays a steep almost featureless continuum, with strong CO band heads and $H_2O$ broad-band absorption features, and Br$\gamma$ line in emission. A later spectrum reveals more absorption features, allowing us to estimate $T_{\rm eff}$~3200 K, $M_*$~0.25 $M_\odot$, and $\dot{M}_{acc}$~$1.2\times10^{-6}$ $M_\odot$ yr$^{-1}$. This makes it one of the lowest mass YSOs with a strong outburst so far discovered. We are carrying on new observations at ESO/VLT to study this rare phenomenon.

### 1.2.4 NIR spectroscopic survey of jets from massive YSOs

*A. Caratti o Garatti, B. Stecklum (Tautenburg), C. Davis (JAC), H. Linz (MPIA), T. Stanke (ESO), and H. Zinnecker (AIP).*

The detection and study of jets and outflows from high-mass young stellar objects (HMYSOs) is of primary importance to understand the mechanism which produces massive strars. We undertook an unbiased spectroscopic follow-up of the $H_2$ emissions detected during our previous imaging runs (ESO-NTT/SofI, TNG/NICS), to clarify the nature and the origin of such emissions (shock vs fluorescence; jet vs photo-dissociation region), derive their excitation conditions (T, $A_V$), and the flow properties (mass, mass ejection rate, $H_2$ luminosity), correlating them with the evolutionary stage of the driving YSO.

### 1.2.5 Observing Outflows close to the Ejection Engine

*D. Coffey, T. Ray (DIAS), Elisabetta Rigliaco, Francesca Bacciotti (Arcetri),Jochen Eislöffel (Tautenburg)*

We have progressed our study of whether we can observe a rotation signature in jets from young stars. We published the results of long awaited observations from the Hubble Space Telescope Imaging Spectrograph (HST/STIS), which had been delayed due to instrument failure and postponement of Servicing Mission 4. These observations are extremely challenging and push the limits of current instrumentation, but have the potential to provide long-awaited observational support for the magneto-centrifugal mechanism of jet launching in which jets remove angular momentum from protostellar systems. The results were of particular interest since they address the previous controversy surrounding T Tauri system RW Aur, which present a paradox of apparently counter-rotating jet and disk. This paradox cast a shadow over the rotation interpretation of differences in Doppler shift between the two sides of the jet as it propagates. These new data reveal that the slope of the Doppler profile transverse to the jet axis is not in the same direction in the approaching jet lobe as has been measured in the receding jet lobe 8 years earlier. Furthermore, the slope disappears six months later. Overall, in the case of RW Aur, measurements are not consistent with a simple jet rotation interpretation. Indeed, given the renowned complexity and variability of this system, it now seems likely that any rotation signature is confused by other influences, with the inevitable conclusion that RW Aur is not suited to a jet rotation study. We continue our jet rotation study of other jet-disk systems, via GEMINI/NIFS data obtained in the infrared of two T Tauri jets for which we already know the sense of disk rotation.

### 1.2.6 MIRI - the Mid-Infra-Red Instrument for the James Webb Space Telescope

*T. Ray, J. Morin, A. Scaife*

**MIRI development environment** The development framework for MIRI-EC software developers (engineered by JM in 2010) has been maintained and upgraded to provide enhanced functionalities. This environment includes the code repository architecture, documentation and testing framework, reference code examples as well as the software installation procedures for all the supported platforms. It ensures that the requirements in terms of code documentation, quality and availability can be fulfilled. The corresponding technical documentation is available online for MIRI-EC and STScI developers and has been regularly updated. JM has presented the MIRI development environment in a poster at the conference Euroscipy 2011 (Paris, France, 25–28 Aug). A technological review of the libraries and software design methods presented at this conference has been by presented by JM to the rest of the MIRI-EC software group (Leiden, Netherlands, 5 Sep).

**Support for simulators and analysis software** JM has continued supporting the development of SCASim, which has fully taken advantage of the new development environment. The performed tasks include software design, python coding, and support for usage of the environment. SCASim simulates the response of the MIRI Sensor Chip Array to a given illumination map. It has been adapted from a previous implementation included in SpecSim (the Medium Resolution Spectrometer Simulator), with the aim to provide a unique tool for the simulators developed for the various instrument modes. SCASim has been used during the flight model performance test campaign that occurred in Spring and Summer 2011.

**Common tools and data products definition** The various MIRI software components need a number of common tools including various levels of data products (corresponding e.g. to science data for different instrument modes, at different processing levels). The work initiated in 2010 has been pursued with further integration of the first functional modules in the aforementioned SCA simulator. Development of the next modules has gone through the following steps: from the requirements drawn in 2010, JM has presented several solutions for the MIRI data products that have been discussed with the rest of the software team. Design choices have been made, they are summarized and justified on the MIRI wiki pages.

### 1.2.7 Global simulations of fully convective stars

*J. Morin, B. Dintrans (Toulouse)*
3D direct numerical simulations of fully-convective stars have been performed using the PENCIL CODE. Their two main aims are (i) to study the effect of the global rotation rate of the star on the amplitude and profile of the internal differential rotation in purely hydrodynamic simulations; and (ii) to study dynamo action in MHD simulations, in order to determine how the properties of the field depend on rotation and (ii) the effect of the generated magnetic field on convection and differential rotation.

### 1.2.8 Weak and strong field dynamos from the Earth to the Stars

*J. Morin, E. Dormy (ENS Paris), M. Schrinner (ENS Paris), J.-F. Donati (Toulouse)*
Observations of magnetism in very low mass stars recently made important progress, revealing characteristics that are now to be understood in the framework of dynamo theory. In parallel, there is growing evidence that dynamo processes in these stars share many similarities with planetary dynamos. We investigate the extent to which the weak-field versus strong-field bistability predicted for the geodynamo can apply to recent observations of two groups of very low mass fully-convective stars sharing similar stellar parameters but generating radically different types

of magnetic fields (strong dipolar field *vs* weak multipolar). We show in particular that (i) the amplitude of the observed large-scale magnetic field in the dipolar regime is compatible (in order of magnitude) with theoretical expectations for a strong-field dynamo branch. (ii) The observed gap between the typical field strengths in the dipolar and multipolar regime is consistent with theoretical expectations based on two different force balances in the two regimes [64].

### 1.2.9 Modelling coronal emission from spectropolarimetric observations

*J. Morin, G. Hallinan (Berkeley), M. Jardine (St Andrews),P. Lang (St Andrews), A. Vidotto, J.-F. Donati (Toulouse)*

The recently discovered radio pulses on ultracool dwarfs have been attributed to electron cyclotron maser instability (ECMI) associated with the presence of strong large-scale magnetic fields. Similar pulses have been observed on a fully convective M4 dwarf and are compatible with the large-scale topology extrapolated from Zeeman-Doppler Imaging. This preliminary work is being pursued, contemporaneous radio and spectropolarimetric observations allow us to model more accurately the ECMI emission and disentangle pulses from flares. We also investigate the evolution of the pulses properties in order to assess the potential radio observations of ECMI emission to study stars out of reach of spectropolarimetry. In parallel, models of stellar coronae are developed from surface magnetograms obtained with ZDI (Zeeman-Doppler Imaging). They allow us to investigate how the change in magnetic topologies that is observed close to the fully convective transition impacts the coronal emissions observed at X-ray and radio wavelengths [Lang et al., submitted].

### 1.2.10 Can we predict the global magnetic topology of a PMS star from its position in the HRD ?

*S. Gregory (Caltech), J.-F. Donati (Toulouse), J. Morin, G. Hussain (ESO), N. Mayne (Exeter), L. A. Hillenbrand (Caltech), M. Jardine (St Andrews)*

Zeeman-Doppler imaging studies have shown that the magnetic fields of T Tauri stars can be significantly more complex than a simple dipole and can vary significantly between sources. Using the observational data as a basis, we argue that the general characteristics of the global magnetic field of a pre-main sequence star can be determined from its position in the Hertzsprung-Russell diagram, across which there are four distinct magnetic topology regimes. This idea is supported by observations of main sequence M dwarfs which exhibit similar relations between the topology of their surface magnetic field and their internal structure. If the magnetic topology trends across the Hertzsprung-Russell diagram are confirmed they may provide a new method of constraining pre-main sequence stellar evolution models, while also allowing the selection of interesting targets in order to optimize future spectropolarimetric observing campaigns [Gregory et al., submitted].

### 1.2.11 Magnetic monitoring of Sun-like stars

*A. Morgenthaler (Toulouse), P. Petit (Toulouse), J. Morin, M. Auriere (Toulouse), B. Dintrans (Toulouse)*

A sample of 19 solar-type stars, probing masses between 0.6 and 1.4 solar masses and rotation periods between 3.4 and 43 days, was regularly observed using the NARVAL spectropolarimeter between 2007 and 2011. The Zeeman-Doppler Imaging technique is employed to reconstruct the large-scale photospheric magnetic field structure of the targets and investigate its long-term temporal evolution. The first results of this project reveal short magnetic cycles in several stars, showing up a succession of polarity reversals over the timespan of our monitoring. Preliminary trends suggest that short cycles are more frequent for stellar periods below a dozen days and for stellar masses above about one solar mass. The cycles lengths unveiled by the direct tracking of polarity switches are significantly shorter than those derived from previous stud-

ies based on chromospheric activity monitoring, suggesting the coexistence of several magnetic timescales in a same star [63].

### 1.2.12 The (Reverse) Luminosity Problem

*A. Scaife, R. Ainsworth, T. Ray (DIAS) & the AMI Consortium*

The evolutionary stages of low-mass star formation are reasonably well defined, although a number of open questions still remain. One important uncertainty is the behaviour of the luminosity distribution at low and very low luminosities. The classic 'luminosity problem' has been known for some time (Kenyon et al. 1990), where the minimum accretion luminosities produced by the standard spherical collapse model (Shu 1977) are up to several orders of magnitude larger than those observed for embedded protostars. This problem has been emphasised by recent star formation surveys, notably that of the *Spitzer Space Telescope* (Evans et al. 2003), and non-steady accretion, starting in the earliest protostellar stages, is currently the best solution to this discrepancy (Kenyon & Hartmann 1995; Young & Evans 2005; Enoch et al. 2007). The luminosity problem is most difficult to rectify in very low luminosity objects (VeLLOs; Young et al. 2004; Dunham et al. 2008) with extreme luminosities $L_{\rm int} \leq 0.1\,{\rm L}_{\odot}$. The nature of these objects is unclear, whether they are young Class 0 protostars which are just powering up, or are more evolved but in a low accretion state (Dunham et al. 2008; Evans et al. 2009). The existing sample of VeLLO sources, although expanded by *Spitzer* (Dunham et al. 2008), is in no way complete. VeLLOs are difficult to confirm as protostars in the infrared due to their low luminosity and embedded nature, and measuring their molecular outflows can be problematic as exemplified by the case of L1014 (Bourke et al. 2005; Crapsi et al. 2005). It is also the case that VeLLOs are often found in cores which are not only assumed to be starless, but which were also not believed to be approaching collapse (Bourke et al. 2006). Nevertheless, identifying a complete sample of these low luminosty embedded protostars is vital for understanding low mass star formation.

A solution to the luminosity problem has been proposed as a non-steady or episodic mass accretion rate onto such objects (e.g. Kenyon et al. 1990; Dunham et al. 2008), and more recently it has been shown using radiative transfer models including both time dependent accretion rates and episodic accretion bursts that the observed distribution of protostars at low luminosities can in fact be reconciled with predictions (Dunham & Vorobyov 2011). This work showed that in order to match the observational data both non-steady accretion components were necessary, notably that neglecting bursts of episodic accretion reduced the agreement between the model and the data. A further interesting result of this work was the prediction of a 'reverse luminosity problem'. This discrepancy exhibits as a theoretically predicted *overabundance* of objects with $L_{\rm int} \leq 0.1\,{\rm L}_{\odot}$ relative to the observed numbers. Currently this difference is ascribed to observational completeness issues at low-luminosities, however, further accurate comparison to models below $0.1\,{\rm L}_{\odot}$ will not be possible without further observational data specifically targeted at identifying and characterizing the very low luminosity population of embedded protostars.

Radio emission from ionized gas in the vicinity of these young objects is a good method for detecting (very-) low luminosity objects (LLOs), as their surrounding dust cores are optically thin to longer wavelength radio emission, and radio surveys (e.g. Scaife et al. 2011a; b; c) have shown that objects with luminosities below the limit for spherical accretion are consistently detected at the 80 per cent level. These detections are important not only for identifying LLOs, but also for understanding the energetics of their evolution. Radio luminosity of YSOs has been shown to correlate well with a number of characteristics derived from other parts of the electromagnetic spectrum - including physical quantities such as internal luminosity, which are only otherwise obtainable following complex modeling. At present the underlying reasons for a number of these correlations are not well understood and further investigations, in addition to improved datasets, are necessary to increase our understanding of

the complex processes leading to these relationships.

In general, the variability of centimeter continuum sources (most probably due to episodic accretion bursts) has not been properly addressed, since observations of sources are limited to a few epochs. There has not been a systematic monitoring campaign of deeply embedded sources to characterize their centimeter variability. In spite of this, there is observational evidence for variability among deeply embedded protostellar sources (Avila et al. 2001; Reipurth et al. 2002), which contributes scatter to the luminosity correlations. In additional to the known variable thermal sources, several nonthermal protostellar sources are known to be highly variable (e.g., T Tauri; Scaife 2011); but, most of those objects are more evolved than deeply embedded protostars.

The timescale over which radio flares toward low-mass stars are observed tends to be minutes to hours. This is very different from the variability observed toward embedded sources where no evidence for short-term variability has been detected. Such sources (e.g. L1014; Shirley et al. 2007) appear to have a nearly constant “flare" flux for at least an 8 hr period. One possibility to explain this discrepancy is that the elevated emission is not due to a flare, but due to rotational modulation of a nonthermal component associated with the magnetic connection between disk and accretion onto the star (i.e. Bieging & Cohen 1989). Although negative spectral indices are expected for nonthermal emission mechanisms, it has been shown that (partially-)unresolved gyrosynchrotron emission from opposite poles of a protostellar magnetosphere will in fact possess a flat, or even positive, spectral index (Kuznetsov et al. 2011). Systematic monitoring campaigns are required to investigate these questions further

We have been undertaking a cm-wave radio follow-up program to the *Spitzer* cores to disks program specifically targeting (Ve)LLO sources (Scaife et al. 2011a; b; c). This extensive program has almost doubled the amount of archival data on the radio emission from low-mass protostellar objects, and these data are made publicly available throughout the Vizier catalogue tool. A number of significant conclusions can already be drawn from these data. As well as confirming that the radio-bolometric luminosity correlation known from higher luminosity objects extends to very low luminosities, a number of completely new correlations have also emerged: (1) *that the radio luminosity is correlated with the internal luminosity of embedded protostellar objects*; (2) *that the radio emission from an increasing number of low luminosity objects cannot be explained by the shock ionization model of Curiel et al. (1989) when drawing correlations with outflow momentum*; (3) *that the radio luminosity is correlated with the envelope mass of embedded objects and that this quantity provides a better tracer than bolometric luminosity*. The most important conclusion from these three points is that the dominant source of radio luminosity for embedded objects is not a consequence of shock ionization in their molecular outflows as previously thought, but is a more global function of **accretion**, which is related to both the internal luminosity and the envelope mass for Class 0 objects.

Further to this, our results have also revealed that there is a significant discrepancy in the detection rates at cm-wavelengths for Class 0 and Class I objects, indicating that the radio emission mechanism in protostellar objects is a function of their evolutionary state. Since accretion in protostellar objects is expected to decrease with age, this conclusion is tied to that drawn independently from the correlation information: radio emission from protostellar objects is a function of accretion.

As part of her PhD thesis, R. Ainsworth has been examining the cm-wave emission from a sample of low-mass YSOs which form part of the eMERLIN legacy project on protostellar jets. She has completed this work (paper submitted) revealing that the sample selected are biased towards high radio luminosities, but otherwise agree well with larger surveys. In addition she has isolated the dominant sources of error in the estimation of radio luminosity and examined how these will affect statistical results from more extended sam-

ples.

### 1.2.13 Circumstellar Disks and Planet Formation

*A. Scaife, R. Ainsworth, T. Ray (DIAS) & the AMI Consortium*

Sub-mm measurements towards circumstellar disks are often used to determine their potential for planet formation, as longer wavelength information provides a unique perspective on the cooler dust in the outer part of the disk. It is this region where protoplanets are expected to form. Alternative methods of disk mass estimation, such as spectral line measurements of molecular gas, are complicated by opacity effects (e.g. Beckwith & Sargent 1993) and require complex models to account for these effects as well as those of depletion (Dutrey 2003; Kamp & Dullemond 2004). Sub-mm and radio measurements are useful not only as a probe of the disk mass itself, but with multi-wavelength data available, they can also be used to determine the evolution of the opacity index as a function of frequency (Shirley et al. 2011a;b) and place constraints on the growth of dust grains in such disks. This can be used to determine whether the timescales assumed in current models of planet formation (e.g. Boss 1998) are consistent with observational data. However, to date the disk masses determined from sub-mm data appear to be too low to agree with theoretical models of planet formation (see e.g. Andrews & Williams 2005), although there are a number of observational caveats associated with these data.

Our observational work has established that for Class I objects the emission at cm-wavelengths is still dominated by the tail of the dust greybody spectrum, rather than alternative radio emission mechanisms, with 70-100 per cent of the cm-wave emission being attributable to thermal dust emission, compared with 20 per cent in Class 0 objects (Scaife et al. 2011d). This supported our earlier results that suggested the radio emission mechanism in protostellar objects is a function of their evolutionary state.

Using a combination of radio and sub-mm data, our work has demonstrated a flattening of the opacity index towards longer (cm-)wavelengths, consistent with a significant population of large dust grains, and in accordance with theoretical models for the collisional growth of grains within circumstellar disks. Deriving disk masses directly from the thermal dust contribution to the cm-wave flux densities under assumptions consistent with the literature we found that *cm-wave disk mass estimates are systematically higher than those determined from sub-mm data* and attributed this difference in disk masses to an increased emission contribution from larger dust grains within the disk at centimetre wavelengths, which is precluded at sub-mm frequencies by opacity effects. Under these assumptions we discovered that disk masses in excess of the lower limit required for giant planet formation (Boss 1998) are recovered in almost 50 per cent of cases when using cm-wave tracers, where none are sufficiently massive from sub-mm data for the same sample.

### 1.2.14 Brown dwarfs and their properties

*A. Scholz, P. Dawson, T. Ray (DIAS), R. Jayawardhana, K. Muzic (Toronto), V. Geers (Zurich), M. Tamura (Tokyo)*

Brown dwarfs are substellar objects intermediate in mass between stars and planets, and crucial for our understanding of star and planet formation. The aim of our SONYC program (short for Substellar Objects in Nearby Young Clusters) is to find and characterise all brown dwarfs in nearby star forming regions. In 2011 we have completed our survey work in $\rho$-Ophiuchus and Chamaeleon-I, presented a new census in NGC1333, and continued to work on the census in Lupus-3. In total, this survey has now discovered $\sim$ 30 previously unknown young brown dwarfs, using data from 8-m class telescopes (Subaru, ESO/VLT). Among them are a handful of objects with estimated masses below 20 Jupiter masses, one of them at around 6 Mjup – one of the lowest mass free-floating objects identified thus far.

As the first part of his Ph.D. thesis, P. Dawson has carried out a brown dwarf survey in the Upper Scorpius star forming region and identified about two dozen candidates based on photometry and proper motions from the UKIDSS project. Combining the census data for all regions, we find that the number ratio between stars and brown dwarfs is not constant in all regions, possibly related to environmental differences in the formation of brown dwarfs.

In addition, we have started projects to exploit the newly released data from the WISE satellite to determine the lifetimes and properties of disks around brown dwarfs.

### 1.2.15 Variability of young stellar objects

*A. Scholz, G. Costigan, T. Ray, A. Natta (DIAS), J. Vink (Armagh), B. Stelzer (Palermo), S. Mohanty (London), L. Testi (ESO Garching)*

Variability is a key property of young stars in their first few Myr after formation, and can be used as a diagnostic of accretion, disk evolution, and magnetic activity. For her Ph.D. thesis, Grainne Costigan investigates the long-term accretion variability of a sample of YSOs in the Chamaeleon-I star forming region based on spectroscopic time series from ESO/VLT. This project was completed in 2011. We found that accretion-related variability occurs on timescales of one week or shorter (or longer than 2 years). The total variations in the mass accretion rate are at most half an order of magnitude over time windows up to 2 years.

Using a photometric and spectroscopic time series obtained at the Calar Alto observatory in 2010, we analysed the curious behaviour of FU Tau A, a very low mass benchmark object in the Taurus star forming region which appears anomalously bright compared with similar-type objects. We found evidence for cool spots corotating with the source, most likely caused by magnetic activity. Furthermore, the objects shows indications for long-term variability due to accretion-related hot spots. These findings bolster the hypothesis that the anomalous brightness can be explained by a combination of magnetically suppressed convection and accretion.

A archive study using data from 2MASS, DENIS, and UKIDSS was carried out to search for long-term variability in a large sample of ~ 600 YSOs. No evidence for accretion outbursts were found, which puts a lower limit of $\sim 2000-2500$ years on the duty cycle of accretion bursts. In general, strongly variable objects with $\Delta K > 0.5$ mag are rare (2-3%). These findings allow us to put strong limits on the contribution of variability to the ubiquitously observed scatter in HR diagrams and to the errors in luminosity estimates.

### 1.2.16 Outflow Activity in the Brown Dwarf Mass Regime

*E. Whelan, T. Ray (DIAS), F. Bacciotti (Arcetri), C. Dougados (Grenoble), J-L. Monin (Grenoble), S. Maddison (Swinburne), A. Natta (DIAS/Arcetri)*

The formation mechanism of brown dwarfs (BD) is currently an open question in the field of star formation. As BDs occupy the gap between solar mass stars and planets this question has garnered much attention in recent years. The most logical approach is to observe key processes involved in the formation of solar mass stars i.e. accretion, outflow activity and variability, at BD masses. In particular, we have been leading a study of BD outflow activity. This began with the first confirmed detection of a BD outflow made by us in 2005 (Whelan et al. 2005). These initial observations were done at optical wavelengths and targeted forbidden emission lines like [O I]$\lambda$6300. Over the last number of years we have been developing this work by increasing the known sample of BD outflows and through expansion into other wavelength regimes e.g. near infrared (NIR) and sub-millimeter (sub-mm). As outflows act as an indirect probe of the central engine observations of outflow activity can provide details important for understanding BD formation. For example our observations to date suggest that the mass outflow to accretion rate in BDs is significantly higher than in solar mass stars. In solar

mass young stars $\dot{M}_{acc}/\dot{M}_{out}$ is typically ~ 10% however in BDs the rates were found to be comparable (Whelan et al. 2009) or in a subsequent study ~ 50% (Bacciotti et al. 2011). Work aimed at constraining $\dot{M}_{acc}/\dot{M}_{out}$ in young BDs is ongoing.

In 2011 we grew our research into BD outflows, firstly through the use of X-Shooter, the new instrument on the ESO VLT. X-Shooter provides simultaneous NIR, optical and UV spectra and hence is an important tool for the study of jets and outflows. Specifically X-Shooter observations allow us to make more accurate estimates of $\dot{M}_{acc}/\dot{M}_{out}$ in a sample of BDs. One paper was published in 2011 (Bacciotti et al 2011) and work is continuing. In addition, in 2011 we began a project to investigate BD molecular outflows. As a first step we did a survey of the $^{12}$CO(2-1) emission in a sample of 16 BDs with the aim of searching for extended molecular emission. All the BDs previously associated with [O I]$\lambda$6300 emission showed evidence of the presence of a molecular outflow. Observations were carried out with the IRAM 30 m telescope in July 2011. A paper is currently in preparation and follow-up observations with the Plateau de Bure interferometer and the SMA are underway / planned. In addition, further time on the 30 m has been granted to observe a second large sample of BDs. Finally in 2011 observing time was granted on the Keck telescope to search for evidence of outflow activity in a sample of Taurus BDs. However observations were unsuccessful due to poor weather and will likely be re-scheduled in 2012.

### 1.2.17 Using AO-assisted Integral Field Observations and Spectro-astrometry to Investigate the Launching of Jets from Young Stars

*E. Whelan, C. Dougados (Grenoble), S. Cabrit (Observatoire de Paris), M. Benisty (Grenoble), L. Podio (Grenoble), F. Bacciotti (Arcetri), T. Ray (DIAS), C. Davis (Joint Astronomy Centre, University of Victoria, Canada)*

While great strides have been made in our understanding of how jets from young stars are launched, collimated and interact with the ambient medium of the driving source, open questions remain and high angular resolution observations on the scale of the central engine are needed. We have been using the techniques of AO-assisted integral field spectroscopy (AO-IFS) and spectro-astrometry (SA) to study the jet launch regions of a sample of young stars including classical T Tauri stars (CTTSs), Herbig Ae/Be stars and FU Orionis stars (FUOR). Jets from CTTSs have been much studied as the optically visible nature of these low mass protostars makes their central engines particularly accessible to observations. In addition, they are numerous in near-by star forming regions. Herbig Ae/Be stars in contrast are less understood and outflows from FUOR have only recently been investigated (Whelan et al. 2010). In order to get an accurate picture of star formation, activity must be investigated across a range of masses and mass accretion rates from BDs to the Herbig Ae/Be stars. AO-IFS is an extremely useful technique as it provides spectro-images (images over a very narrow wavelength range) at high angular resolution. SA offers spatial information on milli-arcsecond scales and when combined with AO-IFS scales reached are a fraction of a milliarcsecond. We are particularly interested in the origin of permitted emission lines such as H$\alpha$ or Br$\gamma$.

Several important projects were started in 2011. For example a multi-faceted study of the RW Aur protostellar system was begun. RW Aur was one of the first CTTSs to be observed and studied. It has many interesting properties including a strong mass accretion rate, highly variable permitted emission and an asymmetric jet. AO-IFS observations produced stunning near-infrared spectro-images of the RW Aur jet at $\approx 0\farcs1$ angular resolution. Interestingly the jet shows evidence of wiggling which points to a close companion to RW Aur. The presence of a companion has already been invoked to explain the variability of RW Aur. In addition, SA is also being used to probe the origin of key permitted lines e.g H$\alpha$ emitted by RW Aur. The main result of this study is that the bulk of the H$\alpha$ emission is tracing a wide-disk wind which we trace to within 5 mas

or ≈1AU of the star. Two papers are currently in preparation (Whelan et al. 2012a,b). We are also studying the Herbig Ae/Be stars HD163296 using SA and interferometry (Benisty et al. 2012). The aim of this work is to understand the origin of the Br$\gamma$ line and to compare with H$\alpha$. Finally in 2011 time on Gemini/ NIFS was granted to do NIR AO-IFS and 2D SA of a large sample of protostars including CTTS, Herbig Ae/Be stars and FUOR.

## 1.3 General Theory

### 1.3.1 Magnetic field amplification by cosmic ray pressure instabilities

*L. Drury and T. P. Downes*

Magnetic field amplification in the shock precursors created by strong particle acceleration is now thought to be an essential aspect of cosmic ray production in supernova remnants and may well also be essential for the production of the ultra-high energy cosmic rays in extra-galactic sources. Attention to date has mainly focussed on the current-driven plasma instability identified by Bell, but this suffers from the problem of amplifying the field on scales small compared to the gyro-radius of the driving particles. As pointed out by Malkov there are alternatives, and in particular the acoustic instability identified by Drury and Falle is a promising candidate. A simple toy model was identified to study the impact of this process on magnetic field amplification and preliminary three dimensional computer simulations performed. These results were presented at the International Cosmic Ray Conference in Beijing.

### 1.3.2 Mechanics and kinetics in the Friedmann-Lemaitre-Robertson-Walker space-times

*F. Aharonian, and S. Kelner, A. Prosekin (MPIK, Heidelberg, Germany)*

Using the standard canonical formalism, the equations of mechanics and kinetics in the Friedmann-Lemaitre-Robertson-Walker (FLRW) space-times in Cartesian coordinates have been obtained. The transformation law of the generalized momentum under the shift of the origin of the coordinate system has been found, and the form invariance of the Hamiltonian function relative to the shift transformation has been proved. The derived equations allow one to shift the origin of the coordinate system to the point of location of the observer. The space in the vicinity of this point can be considered as a Euclidean one which makes straightforward the interpretation of calculations. For the distribution function in the phase space, the general solution of the collisionless Boltzmann equation has been found. The results of this work can be used for treatment of evolution of the distribution function of particles arriving from the cosmologically distant objects. We discuss, in particular, two important cases of astrophysical interest: (i) the homogenous distribution particles taking into account energy losses, and (ii) the spherically symmetric case with arbitrary angular distribution. While the first problem is linked to the diffuse distributions of particles produced at cosmological epochs, the second one is relevant to the discrete astrophysical objects.

### 1.3.3 Electron acceleration by plasma shocks

*G. C. Murphy, L. O'C. Drury, M. Dieckmann (U. Linkoping)*

Gamma ray bursts (GRBs) are thought to originate from highly relativistic jets. The fireball model predicts internal shocks in the jets, causing magnetic field to be amplified & particles to be accelerated. We model the effects of an asymmetric density configuration for an internal plasma collision in a quasi-parallel magnetic field. We measured electron acceleration & found that a tenuous population of electrons is accelerated to Lorentz factors of ~ 300 - close to energy equipartition with ions. We found that the filaments did not remain static, but were deflected by the Lorentz force & rolled up into small vortices, which themselves merge to form a larger current vortex. By increasing the runtime of simulations, we derived electron distributions which

were injected into one-zone models to predict synthetic observations.

### 1.3.4 Filament formation in counterstreaming plasma

*G. C. Murphy, L. O'C. Drury, M. Dieckmann (U Linkoping), G. Sarri, K. Quinn, M. Borghesi (QUB)*

The magnetic fields which are inferred in observations of gamma ray bursts and supernova remnants can originate from plasma effects. 2D particle simulations model the filamentation instability. Our results show that exponential growth is followed by saturation of the magnetic field. The composition of the beams affects the growth of the electrostatic field and the in-plane current coherency and correlation scale. The growth rate is close to the analytical value of $\beta\sqrt{2/\Gamma_b}$.

### 1.3.5 PRACE particle-in-cell scalability testing

*Gareth C. Murphy, M. Browne, G. Civario (ICHEC)*

0.5 million core hours were awarded to investigate the performance of the PIC plasma simulation code (PSC) on two Tier-0 architectures. PSC was shown to scale well on JUGENE (Julich) and CURIE (France). We found that the proportionally more time was spent in global MPI communication during timing routines in the code. These could be reduced in frequency causing a speedup of 14.9%. We found proof of code scaling to 32,000 cores on Jugene. We gained experience on scaling testing and identifying bottlenecks in the parallel algorithms. The speedup of 14.9% was maintained on higher numbers of cores, resulting in near-linear strong scaling.

## 2 Invited talks

- F. Aharonian
  - Exploring the Very High Energy Sky with H.E.S.S, Rossi Prize talk at the American Astronomical Society meeting, Jan 12, Seattle, USA
  - Predicting Galactic Neutrino Fluxes from Gamma Ray Data, XIV International Workshop on Neutrino Telescopes, March 15-18, Venice, Italy
  - High Energy Gamma Ray Astronomy, 3rd Roma International Conference on Astroparticle Physics, May 25-27, Rome, Italy
  - Probing Cosmic Ray Accelerators With Gamma Rays and Neutrinos, 32nd International Cosmic Ray Conference, August 11-18, Beijing, China
  - Gamma Rays: Physics Interpretation, 12th International Conference on Topics in Astroparticle and Underground Physics (TAUB 2011), September 5-9, Munich, Germany
- V. Bosch-Ramon
  - Multifrequency Behavior of Microquasars in the GeV-TeV era: A review, Frascati Workshop 2011, Vulcano, Italy, May.
  - Non-Thermal Emission from Galactic Jets, High-energy phenomena in relativistic outflows III, Barcelona, Spain, June.
  - Particle acceleration in microquasars and binary systems, 13th ICATPP Conference, Como, Italy, October.
  - Multi-GeV astrophysics in gamma-ray binaries, Multi-GeV astrophysics with ground-based detectors, Dublin, Ireland, December.
- A. Caratti o Garatti
  - 16/02/2011 -Talk on ***"Investigating Class I/II YSOs in L1641 through combined optical/IR spectroscopy"*** at the *"Thüringer Landessternwarte Tautenburg"*, Tautenburg, Germany
  - 24/02/2011 -Talk on ***"Investigating Class I/II YSOs in L1641 through combined optical/IR spectroscopy"*** at the *"Max Planck Institut für Radioastronomie"*, Bonn, Germany
  - 2/03/2011 -Talk on ***"Investigating Class I/II YSOs in L1641 through combined optical/IR spectroscopy"*** at the Department of Physics *"Universität zu Köln"*, Cologne, Germany
  - 18/05/2011 -Talk on ***"Massive jets from massive YSOs"*** at the Department of Physics and Astronomy of the *"University of Leeds "*, Leeds, United Kingdom
  - 01/06/2011 -Talk on ***"Massive jets from massive YSOs"*** at the *"Max Planck Institut für Radioastronomie"*, Bonn, Germany
  - 17/11/2011 -Talk on ***"Massive jets from massive YSOs"*** at the *"Thüringer Landessternwarte Tautenburg"*, Tautenburg, Germany
- D. Coffey
  - Invited conference talk, 'The Enigma of Jets and Outflows from Young Stars', The Indian Institute for Astrophysics, Bangalore, June 2012.
- L. Drury

- Cosmic Rays, Gamma Rays and Galactic Neutrino Astronomy, VLVnT11, Erlangen, Germany, 13 October.

- G.C. Murphy
  - Magnetic field amplification and electron acceleration in mildly relativistic protoshocks , Niels Bohr Institute, Denmark, 16 November

- A. Scaife
  - The LOFAR Magnetism Key Science Project, seminar, University of Manchester, UK, 2 January.
  - The LOFAR Magnetism Key Science Project, seminar, University of Hertfordshire, UK, 8 February.
  - The Application of Bayesian Methods in Radio Astronomy, seminar, University of Newcastle, UK, 1 April.
  - Compressed Sensing for Rotation Measure Synthesis, CALIM 2011, Manchester, UK, 26 July.
  - Next Generation Polarization Science (review), International Union of Radio Science General Assembly, Istanbul, Turkey, 15 August.
  - The Application of Compressed Sensing Techniques in Radio Astronomy (review), International Union of Radio Science General Assembly, Istanbul, Turkey, 17 August.
  - Prospects for Compressed Sensing Reconstruction in Rotation Measure Synthesis, BASP, Villars, Switzerland, 8 September.
  - Using Radio Emission from Low-Mass Protostars to Tackle the Luminosity Problem, seminar, Royal Observatory, Edinburgh, UK, 30 November.

- A. Scholz
  - Brown dwarfs vs. stars, G2000 seminar, University of Toronto, Canada, November.
  - Young brown dwarfs: testing star and planet formation, RG seminar, CfA/Harvard, Boston, USA, December.

- E.T. Whelan
  - Disks, Accretion and Outflows in Brown Dwarfs.
  - Astronomische Gesellschaft 2011, âĂIJFormation, atmospheres and evolution of brown dwarfsâĂİ, September 2011

# 3 Externally funded projects and grants of resources

## 3.1 Observing Runs: Completed or Awarded in 2011

- A. Caratti o Garatti
  - **An REM/TNG study of IR variability in embedded Young Stellar Objects** *Aug 2010 - Jan 2011* - 4 hrs + 96 hrs at TNG/REM, service. PI/CoI: **Caratti o Garatti A.**, Massi F., Garcia Lopez R., Nisini B., Scholz A., Antoniucci S., Giannini T., Coffey D., Ray T.

- **An REM/Spitzer survey of the optical/IR variability of Young Stellar Objects in Serpens** *Apr 2011 - May 2011* -30 hrs at REM, service. PI/CoI: **Caratti o Garatti A.**, Covey K., Garcia Lopez R., Scholz A., Stauffer J., Morales-Calderon M., Rebull L., Gutermuth R.
- **Revealing the nature of the outbursting Class I protostar [CTF93]216-2 and its environment** *Oct. 2011 - Mar. 2012* - 8 hrs at VLT (SINFONI + ISAAC) service. PI/CoI: **Caratti o Garatti A.**, Garcia Lopez R., Stecklum B., Scholz A., Nisini B., Eislöffel J., Antoniucci S., Giannini T., Ray T.
- **Origin of the Br$\gamma$ emission in Young Stars: AMBER MR-K observations of three Herbig AeBe stars** *Febrauary 2011* - 2.5 hrs at VLTI (AMBER). PI/CoI: Dougados C., Bacciotti F., Benisty M., Podio L., Whelan E., Antoniucci S., Alecian E., **Caratti o Garatti A.**, Garcia P., Nisini B., Malbet F.
- **Jet launch and properties of the most luminous $H_2$ YSO outflow** *April 2011* - 4 hrs at VLT (SINFONI + ISAAC). PI/CoI: Stecklum B., **Caratti o Garatti A.**, Linz H.

- D. Coffey
  - ESO VLTI / AMBER: 1 night completed in 01 Apr 2011 (GTO 087.C-0604(A)
  - ESO VLTI / AMBER: 1 night completed in 03 Apr 2011 (GTO 087.C-0598(A)

- J. Morin
  - **Improving detection limits of planets orbiting moderately active M dwarfs with polarimetric monitoring**
    *May–Aug 2011, ESO/HARPS, 4.5 nights, visitor (087.C-0412). PI/CoI: J. Morin, J.-F. Donati (Toulouse), X. Delfosse (Grenoble), T. Forveille (Grenoble)*
  - **Understanding the M dwarf Radius Discrepancy at the Fundamental Level: Magnetic Field Mapping of Two M dwarf Eclipsing Binaries**
    *Jan 2012, CFHT/ESPaDOnS, 40 hr, service (11BF14, 11BF97). PI/CoI: J. Morin, L. Hebb (Vanderbilt Univ.), G. Hussain (ESO), K. Stassun (Vanderbilt Univ.), J.-F. Donati (Toulouse)*

- A. Scaife
  - Effelsberg telescope: 40 hours completed (87-10)
  - Green Bank telescope: 105 hours awarded, 39 hours completed (GBT11B-068)
  - ATCA telescope: 14 hours awarded, 14 hours completed (C2468)
  - eMERLIN telescope: 862 hours awarded (eMERLIN legacy Super-CLASS project)
  - LOFAR telescope: 12 hours completed (LEA192)
  - AMI telescope: 500+ hours awarded and completed (various)

- A. Scholz
  - Subaru telescope: 1 night completed (S11B-053)
  - ESO/VLT: 8.5h awarded for 2012 (089.C-0432), 9.3h awarded for 2012 (089.C-0311), 9.1h awarded for 2012 089.C-0652, 8h completed (088.C-0413), 10.2h completed (087.C-0386)
  - ESO/VISTA: 100h completed (087.D-0829)
  - ESO/2.2m: 40h granted from MPI for 2012

- IRTF: 3 nights granted (2012A005)
- SMARTS consortium: 4 nights observing time granted for 2012

- E.T Whelan
  - IRAM 30 m: 1 night completed July 2011, 1 night awarded 2012 (04-11-Monin)
  - Plateau de Bure: 3.0h awarded for 2012 (V070-Whelan)
  - ESO/VLT: awarded for 2011/2012, 3.5 hrs (288.C-5013(A)), 0.5 hrs (086.C-0080(B)), 9.3 hrs (089.C-0311(A))
  - Keck/HIRES: 1 night completed in 2011
  - Gemini/NIFS: 10.5 hrs granted (GN-2012A-Q-116)

### 3.2 Supercomputer Access in 2011

- G.C. Murphy
  - Shocks: Understanding Relativistic Plasmas Acceleration Systems, PRACE (Jugene and Curie), 500,000 hours Feb-Aug 2011

### 3.3 Current Research Project Grants

- A. Caratti o Garatti
  - **Marie Curie European Reintegration Grant**, FP7-PEOPLE-2009-RG, Proposal N 249157, title: 'A photometric and spectral survey of young stars in nearby star-forming regions: towards a revised evolutionary sequence based on quantitative accretion/ejection diagnostics'
- D. Coffey
  - Italian Space Agency grant (6 month postdoc, E. Rigliaco)
- A. Scholz
  - Science Foundation of Ireland, RFP grant 10/RFP/AST2780 (1 postgraduate student)

### 3.4 Proposals submitted

- Bosch-Ramon, V.
  - European Research Council, Starting Grant (pending)
- Scaife, A.
  - European Research Council, Starting Grant (pending)
- Scholz, A.
  - European Research Council, Starting Grant (pending)

# 4 Contributions to Teaching

- J. Morin
  - Evry Schatzman 2011 School, “Low-mass stars and the transition stars/brown dwarfs” (2 lectures), Roscoff, France, 11–16 Sep.
- G. C. Murphy
  - “Introduction to Numerical Methods” (24 lectures), UCD School of Mathematical Sciences, Dublin
  - “Introduction to Astrophysics” (18 lectures) , Loughborough University, UK
- E.T Whelan
  - NUI Maynooth, 6 lectures, “Hot Topics in Astrophysics"

# 5 Community Service, Awards and Distinction

- Bosch-Ramon, V.
  - Associated member of the MPIK high-energy astrophysics theory group (Heidelberg, Germany)
  - Associated member of the group of relativistic astrophysics and radioastronomy (La Plata, Argentina)
  - Associated member of the group of high-energy galactic sources (Barcelona, Spain)
- L. Drury
  - Election as President of the Royal Irish Academy, 16 March.
- A. Scaife
  - Young Scientist Award from the International Union of Radio Sciences (URSI).
- D. O’Sullivan
  - continued as a member of the panel of experts chosen to advise the Government Chief Scientific Adviser.
  - continued role on the ESA Theseus team which is drawing up a strategy for future human space travel
- A. Scholz
  - press release for the SONYC project, issued by the Subaru telescope: ’ "Failed Stars" Galore with One Youngster Only Six Times Heftier than Jupiter’, October 2011 (this release was covered by numerous international press outlets, including MSNBC, space.com, wired.com.

# 6 Contributions to research infrastructures

## 6.1 National Capability Computing Initiative

The agreed three year period for operation of the two Blue Gene systems came to an end at the end of 2010 and both systems were powered down in early January 2011. An expression of interest in taking over the P-system was received from IBM and TCD and following extended discussions with the funding agencies it was eventually agreed to transfer ownership of the P-system to TCD for a nominal sum of €1. The transfer took place in August 2011. A review of the impact of the initiative concluded that it had met, and in many areas exceeded, the *ex ante* expectations for the project.

### 6.1.1 e-INIS

During 2011 the e-INIS project continued to progress well and has now been very successful in improving the quality and quantity of shared ICT research infrastructure available in Ireland.

**High Performance Computing (HPC)** The provision of service (compute, data management and visualization) for users in Ireland and their international collaborators continues with a large number of publications enabled by resources managed by TCHPC and ICHEC in this period. Stokes, Stoney, Kelvin and the BlueGene/P resource are facilitating enhanced research output.

The National Compute Service operated by ICHEC, on infrastructure majority or wholly funded under e-INIS (Stokes and Stoney), continued to see widespread use from across the sector. The TCHPC capability-lite infrastructure (Kelvin) became operational and is being used by researchers from several third level institutions including TCD, NUIM, UCD and UCC/Tyndall.

The Grid-Ireland Operations Centre has installed a 20TF GPU-based capacity computing enhancement at their Grid site in TCD. The 32-GPU/64-core cluster came online in Jun-2011.

**Networking** The e-INIS optical network now has connections from DIAS, NUIG, UCC and UCD. The 10Gbit/s network, operated by HEAnet, has a separate routed connection to the rest of HEAnet and onward via GEANT which enables the increased throughput particularly important to data-intensive research.

**Data Management** The area of Research Data Management has become a hotbed of activity and the pilot e-INIS data store has played a considerable role in supporting the sharing and re-use of data among high profile national and international collaborations. During 2011 the available storage volume grew to exceed one Petabyte (1 million gigabytes) adding significant research capacity to the Irish community.

Due to continued demand from the user community, further expansion of the data management service will be required over the remainder of the project and we expect to compile a number high profile use cases and associated publicity material. Access and Service Support The e-INIS Federated Access service was formally launched as Edugate in November 2010. At the end of September 2011, it had 31 services and 25 identity providers, representing 90% of staff and students in publicly-funded higher education institutions. As per our stated objective in the first year of production, we have successfully attracted some of the world's leading publisher and electronic journals as service providers.

The identity providers include 6 of 7 universities, and 14 of 15 Institutes of Technology. 100% membership of the HEI sector is expected by October 2011. See http://www.edugate.ie/content/edugate-federation-members for details of services and members.

**Outlook** The reduction in funded staff numbers (due to the exhaustion of project budgets along with the departure of highly skilled personnel to the private sector) will no doubt present additional challenges over the remainder of the project but it has been encouraging to see increased levels of collaboration among partners in an attempt to make up for some of these shortages.

The anticipated restructuring of the national HPC services is expected to bring exciting new opportunities for the long-term sustainable provision of e-Infrastructure in Ireland. During 2012, the e-INIS partners will invest significant effort in developing governance and sustainability plans to ensure that pilot services such as the e-INIS Data Store can be migrated to a long-term production basis within appropriate organisations.

# 7 Institutional partnerships

Signed framework agreements on cooperation are now in place with all three local universities (TCD, UCD and DCU) and regular meetings to coordinate cooperation in research, teaching and outreach activities have been initiated.

# 8 Public Outreach

- Bosch-Ramon, V.
  - Powerful outflows in the Universe, Dunsink Observatory, Dublin, January 2011
  - Black holes: lighthouses of the Universe, Dunsink Observatory, Dublin, November 2011
- Caratti o Garatti, A.
  - 19th of January 2011, Dunsik Observatory, Dublin. Public lecture on 'Stellar evolution'.
- Coffey, D.
  - Evening lecture, 'Disks and jets: observations and unsolved problems', The Indian Institute for Astrophysics, Bangalore, June 2012.
- Coffey, D.
  - Evening lecture, 'Disks and jets: observations and unsolved problems', The Indian Institute for Astrophysics, Bangalore, June 2012.
- L. Drury
  - The 2011 McCrea lecture: "The hundred year mystery of cosmic rays", given on 9 Dec in TCD.
- J. Morin
  - Dunsink Observatory Open Nights, 25 Jan and 15 Mar.
- G.C. Murphy

- Astronomy Ireland Science Week Lecture, Trinity College Dublin, 11 Nov

- Scholz, A.
  - talk 'Brown Dwarfs', Dunsink Observatory, Dublin, December 2011
  - popular science book 'Das neue Lexikon des Unwissens' (in German) published, September 2011

- F. Aharonian
  - "The Extreme Universe", invited lecture at the Inauguration of the Center for Astroparticle Physics 'CAP Geneve, March 9, 2011, Versoix, Switzerland

- E.T. Whelan
  - talk 'Star and Planet Formation', Dunsink Observatory, Dublin, November 2011
  - Interview, Siliconrepublic.com, Science Week 2011

# 9 Conferences, Workshops and Summer Schools Organised

## 9.1 Summer School on High Energy Astrophysics

*Felix Aharonian (DIAS) and Lorraine Hanlon (UCD)*

Local Organising Committee: F. Aharonian, L. Hanlon, V. Bosch-Ramon, R. Byrne, M. Chernyakova, L. Drury, L. Fallon, E.Flood, B. Fox, A. Grace, Jamie Keating, A. Martin-Carrillo, G. Murphy, H. O'Donnell and M. Topinka.

Scientific Advisory Committee: J. Arons, L. Bergstrom, C. Cesarsky, A. Loeb, M. Longair, J. Silk and R. Sunyaev.

Dates: 4th - 15th July 2011

Astroparticle Physics is a new field of research emerging at the intersection of particle physics, astronomy, and cosmology. It aims to answer fundamental questions related to the story of the Universe such as: What is the Universe made of? What is the origin of cosmic rays? What is the nature of gravity? The rapid and exciting progress in this emerging interdisciplinary field is attracting ever growing numbers of students and young researchers. However, currently very few Universities or Research Centers are able to provide systematic courses on different aspects of this rapidly developing field for young researchers entering it. This two-week, 36-lecture course filled this gap by providing a coherent series of advanced lectures on Observational and Theoretical Cosmology, High Energy Non-thermal Galactic and Extragalactic Source Populations, Origin of Cosmic Rays, Particle Acceleration and Radiation Processes. The lectures were given by active researchers who covered the latest developments in their respective areas, while at the same time introducing the basics of the field thereby giving their lectures a pedagogical character. Full details of the programme, including the lectures, can be found at:

http://homepages.dias.ie/~cappa/

The school attracted some 70 students of whom the majority were from outside Ireland.

Figure 4: A group photograph of some of the summer school attendees with the two school directors, Felix Aharonian and Lorraine Hanlon, in the front row.

Figure 5: Animated discussion at the summer school!

## 9.2 Multi-GeV Astrophysics with Ground-Based Detectors

*F. Aharonian, L. Bergstrom (OKC), V. Bosch-Ramon, J. Conrad (OKC), L. Drury and F. Ryde (OKC)*

This workshop was held in Dublin from 12 to 14 December and was the first of a series of small to mid-size scientific meetings dedicated to specific topics of High Energy Astrophysics and Cosmology as a joint initiative of the the Dublin Institute for Advanced Studies and the Oskar Klein Centre for Cosmoparticle Physics, University Stockholm.

The aim of the workshop was a comprehensive discussion of the scientific topics and formulation of main objectives and motivations of study of the sky in the rather narrow, but astrophysically extremely important, energy interval between 10 to 100 GeV, being presently a quite poorly explored energy band of the cosmic electromagnetic spectrum. While the small detection area of the Fermi LAT does not allow adequate photon statistics, the current Cherenkov telescope arrays operate effectively in the energy range above 100 GeV. However, the principal possibility of extension of the Imaging Atmospheric Cherenkov Telescope (IACT) technique towards 10 GeV promises a new breakthrough in gamma-ray astronomy. The relatively large gamma-ray fluxes in this energy interval, together with the huge detection areas offered by the IACT technique, can provide the highest gamma-ray photon statistics compared to any other energy band of cosmic gamma-radiation. This should allow detailed spectroscopic and temporal studies of a broad variety of astrophysical phenomena related to pulsars, compact binary systems, gamma-ray bursts, active galactic nuclei, as well as cosmological issues related to the indirect search for Dark Matter, Diffuse Extragalactic UV Background, and Intergalactic Magnetic fields.

The workshop was attended by 41 participants and used the newly refurbished facilities in Dunsink Observatory as well as the Institute's lecture theatre in Burlington Road.

## 9.3 SKA CALIM 2011, July 25-29, Manchester, UK

The CALIM meeting focuses on progress in algorithms, software and computing aimed at addressing the challenges of calibration and imaging for the Square Kilometre Array (SKA), its pathfinders and other major new radio telescopes such as EVLA, ALMA, LOFAR, ASKAP, MeerKAT, ATA, FAST, MWA, LWA, PAPER/HERA, eMERLIN, GMRT, WSRT/APERTIF etc.

The 2011 meeting was the 6th in a series, following the successful previous meetings held in Dwingeloo (2005), Cape Town (2006), Perth (2008), Socorro (2009) and Dwingeloo (2010). The aim of CALIM is to bring together specialists in the field in order to maintain a coherent strategy for SKA development, consequently it is a highly focused meeting with no general topics addressed. Participation was limited to 50 attendees (excluding local observers) and all major next-generation telescopes were represented by participants from multiple continents.

See http://www2.skatelescope.org/indico/conferenceDisplay.py?confId=171

A. Scaife (DIAS) was one of the nine chairs of the meeting.

# 10 Detailed Bibliography of Publications

Note that where possible hyperlinks have been provided to the journal article and preprint version.

## 10.1 Peer-reviewed Publications in 2011


[1] A. A. Abdo et al. "Discovery of High-energy Gamma-ray Emission from the Binary System PSR B1259-63/LS 2883 around Periastron with Fermi". In: ApJ 736, L11 (July 2011), p. L11. DOI: 10.1088/2041-8205/736/1/L11. arXiv:1103.4108 [astro-ph.HE] (cit. on p. 7).

[2] A. A. Abdo et al. "Fermi Large Area Telescope Observations of Markarian 421: The Missing Piece of its Spectral Energy Distribution". In: ApJ 736, 131 (Aug. 2011), p. 131. DOI: 10.1088/0004-637X/736/2/131. arXiv:1106.1348 [astro-ph.HE].

[3] A. A. Abdo et al. "Insights into the High-energy $\gamma$-ray Emission of Markarian 501 from Extensive Multifrequency Observations in the Fermi Era". In: ApJ 727, 129 (Feb. 2011), p. 129. DOI: 10.1088/0004-637X/727/2/129. arXiv:1011.5260 [astro-ph.HE].

[4] A. Abramowski et al. "H.E.S.S. Observations of the Globular Clusters NGC 6388 and M15 and Search for a Dark Matter Signal". In: ApJ 735, 12 (July 2011), p. 12. DOI: 10.1088/0004-637X/735/1/12. arXiv:1104.2548 [astro-ph.HE].

[5] A. Abramowski et al. "Search for a Dark Matter Annihilation Signal from the Galactic Center Halo with H.E.S.S." In: *Physical Review Letters* 106.16, 161301 (Apr. 2011), p. 161301. DOI: 10.1103/PhysRevLett.106.161301. arXiv:1103.3266 [astro-ph.HE].

[6] V. A. Acciari et al. "Spectral Energy Distribution of Markarian 501: Quiescent State Versus Extreme Outburst". In: ApJ 729, 2 (Mar. 2011), p. 2. DOI: 10.1088/0004-637X/729/1/2. arXiv:1012.2200 [astro-ph.HE].

[7] M. Actis et al. "Design concepts for the Cherenkov Telescope Array CTA: an advanced facility for ground-based high-energy gamma-ray astronomy". In: *Experimental Astronomy* 32 (Dec. 2011), pp. 193–316. DOI: 10.1007/s10686-011-9247-0.

[8] F. Aharonian et al. "Cosmic Rays in Galactic and Extragalactic Magnetic Fields". In: Space Sci. Rev. (Apr. 2011), p. 268. DOI: 10.1007/s11214-011-9770-3. arXiv:1105.0131 [astro-ph.HE].

[9] F. Aharonian et al. "Primary particle acceleration above 100 TeV in the shell-type supernova remnant RX J1713.7 - 3946 with deep H.E.S.S. observations". In: A&A 531, C1 (July 2011), p. C1. DOI: 10.1051/0004-6361/20066381e.

[10] J. Aleksić et al. "A Search for Very High Energy Gamma-Ray Emission from Scorpius X-1 with the Magic Telescopes". In: ApJ 735, L5 (July 2011), p. L5. DOI: 10.1088/2041-8205/735/1/L5. arXiv:1103.5677 [astro-ph.HE].

[11] J. Aleksić et al. "Gamma-ray Excess from a Stacked Sample of High- and Intermediate-frequency Peaked Blazars Observed with the MAGIC Telescope". In: ApJ 729, 115 (Mar. 2011), p. 115. DOI: 10.1088/0004-637X/729/2/115. arXiv:1002.2951 [astro-ph.HE].

[12] J. Aleksić et al. "Observations of the Blazar 3C 66A with the Magic Telescopes in Stereoscopic Mode". In: ApJ 726, 58 (Jan. 2011), p. 58. DOI: 10.1088/0004-637X/726/2/58. arXiv:1010.0550 [astro-ph.HE].

[13] AMI Consortium et al. "10C survey of radio sources at 15.7 GHz - II. First results". In: MNRAS 415 (Aug. 2011), pp. 2708–2722. DOI: 10.1111/j.1365-2966.2011.18925.x.

[14] AMI Consortium et al. "10C survey of radio sources at 15.7 GHz - I. Observing, mapping and source extraction". In: MNRAS 415 (Aug. 2011), pp. 2699–2707. DOI: 10.1111/j.1365-2966.2011.18887.x.

[15] AMI Consortium et al. “AMI-LA radio continuum observations of Spitzer c2d small clouds and cores: Perseus region”. In: MNRAS 415 (July 2011), pp. 893–910. DOI: 10.1111/j.1365-2966.2011.18755.x. arXiv:1101.5514 [astro-ph.GA].

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[24] P. Bordas, V. Bosch-Ramon, and M. Perucho. “The evolution of the large-scale emission in Fanaroff-Riley type I jets”. In: MNRAS 412 (Apr. 2011), pp. 1229–1236. DOI: 10.1111/j.1365-2966.2010.17982.x. arXiv:1011.1653 [astro-ph.HE] (cit. on pp. 6, 7).

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# ANNUAL REPORT 2011

## 1 Report on Research Work

### 1.1 Work by Senior Professors and Collaborators

#### 1.1.1 W. Nahm

**Partition Functions amd Modular Forms**
*(W. Nahm & S. Keegan)*

Werner Nahm and Sinead Keegan constructed more examples of modular q-hyper geometric functions, using cosets of affine Kac-Moody algebras at fractional level. This was motivated by mathematicians who became interested in Nahm's conjecture and asked for more examples. Among them were S. Zwegers and M. Vlasenko, who obtained significant new results on this conjecture. Cooperation with UCD in this area was ended, since Prof. S. Zwegers moved to Germany. This is partially compensated by the move of Masha Vlasenko from Max-Planck-Institute for Mathematics, Bonn to TCD, though her work as lecturer leaves her much less time for research.

Werner Nahm also solved a thirty year old problem in mathematics. Assume that E and F are k-ample vector bundles. Show that their sum and tensor product are k-ample. This was known only under the assumption that E and F are generated by global sections. The method for a key step in the proof was inspired by Feynman graphs.

#### 1.1.2 T.C. Dorlas

**Research overview**

This has been a poor year due to personal circumstances. Hopefully next year will be back to normal. However, an article was written with Ciara Morgan on the product-state capacity of periodic quantum channels, and Pavel Abramskii was supervised and completed his Ph.D. on 'Completeness of $\delta$-Interacting Particles'. Moreover, a course on 'Quantum Mechanics and the Bethe Ansatz' was given at a summer school in Sweden, and some work was done in the following areas:

**Classical capacity of periodic quantum channels**

*(T.C. Dorlas & C. Morgan)*

Together with Ciara Morgan (Singapore) the classical product-state capacity of a particular type of quantum channel was investigated. The channel is simple *periodic*, that is, a given set of completely positive maps $\Phi_1, \ldots, \Phi_L$ is applied in rotation. Such a channel is not 'forgetful', i.e. it has long-term memory, because it matters, even for long times, what was the initial map applied. As a consequence, the strong converse does not hold in general. (In fact, it is not known if the strong converse does hold for the classical capacity of any quantum channel. For the product state capacity, it is known to hold for memoryless channels.) This means that there is a gap between the product-state capacity and the 'strong' capacity, i.e. the rate above

which the error probability tends to 1. We proved that such a gap exists in the case of amplitude damping channel maps $\Phi_i$ and, more interestingly, that there are is a scale of intermediate capacities delimiting ranges in which the error probability tends to multiples of $1/L$.

**Bethe Ansatz**

*(T.C. Dorlas & P. Abramski)*

Together with Pavel Abramski, we devised a new approach to proving scattering completeness for the $n$-particle scattering states of *delta*-interacting particles on a line. We only considered the repulsive case with Hamiltonian

$$H = -\sum_{i=1}^{n} \frac{\partial^2}{\partial x_i^2} + 2c \sum_{1\le i<j\le n} \delta(x_i - x_j),$$

where $c > 0$. The corresponding scattering states are given by

$$\psi_{in}(x_1, \dots, x_n \,|\, k_1, \dots, k_n) = \sum_{\sigma\in S_n} \frac{\psi(x_{\sigma(1)}, \dots, x_{\sigma(n)} \,|\, k_{\sigma(1)}, \dots, k_{\sigma(n)})}{\prod_{1\le r<s\le n} A_{\sigma(r)\sigma(s)}} \times \theta_\sigma(k_1, \dots, k_n),$$

where $A_{ij} = A(k_i - k_j)$ is a certain function of the difference of momenta,

$$A(k) = 1 + \frac{ic}{k},$$

and $\theta_\sigma$ is an indicator function for the domain $k_{\sigma(1)} > \cdots > k_{\sigma(n)}$. The wave function $\psi$ is defined on this domain only and is given by the Bethe Ansatz expression

$$\psi(x_1, \dots, x_n \,|\, k_1, \dots, k_n) = \sum_{\sigma'\in S_n} C_{\sigma'} e^{i[k_{\sigma'(1)}x_1 + \cdots + k_{\sigma'(n)}x_n]}$$

if $k_1 > \cdots > k_n$. One of the advances is that this wave function can be written in operator form as follows:

$$\psi(x_1, \dots, x_n \,|\, k_1, \dots, k_n) = \sum_{\sigma\in S_n} \prod_{\alpha\in D(\sigma)}^{\rightarrow} (A_\alpha + B_\alpha P_\alpha) \times \prod_{\alpha\in D(\sigma)}^{\leftarrow} \tau_\alpha[1\dots n](x)\chi(1\dots n),$$

where $B_\alpha = 1 - A_\alpha$, and $D(\sigma)$ is the collection of pairs of interchanged numbers in $\sigma$,

$$[1\dots n](x) = e^{i(k_1x_1 + \cdots + k_nx_n)},$$

$P_\alpha$ is the transposition of momenta with indices in $\alpha$, and $\tau_\alpha$ is a similar transposition of both momenta and positions. The arrows above the products indicate an ordering such that $\sigma$ can be written as a product of transpositions $\sigma = \prod_{\alpha\in D(\sigma)}^{\leftarrow} \alpha$. Note that this ordering is not unique. Yang first remarked that this representation is independent of the particular order chosen, and he noted that the condition for this to be the case is what is now known as the Yang-Baxter equation. We give a formal proof of this independence.

We prove the completeness of the scattering states in the form of the orthonormality relation

$$\langle \psi_{in}(\cdot|\mathbf{k}')|\psi_{in}(|\mathbf{k})\rangle = \delta(\mathbf{k} - \mathbf{k}').$$

The proof is entirely combinatorial but relies on an as yet unproven lemma.

**Definition of the Feynman path integral**

*(T.C. Dorlas & M. Beau)*

Together with Dr. Mathieu Beau, work was started on a new mathematical approach to the Feynman path integral, defining it as a so-called 'path distribution' on a Hilbert space of paths. This approach was initiated by the late Prof. Erik Thomas (Groningen). However, he formulated as a path distribution on nuclear spaces instead, which is technically more difficult. We hope to use a Fourier transform in

time to reduce the path distribution to a product distribution.

**Quantum spherical model**

*(T.C. Dorlas & I. Lyberg)*

In collaboration with Dr. Ivar Lyberg, a spherical model analogue of the Ising model with transverse field was formulated. It can be solved exactly and turns out to have a similar zero-field phase transition as the original model. Some technical details have yet to be clarified, which in fact does not seem to have been done either for the spherical model itself.

**Lectures on Large Deviations**

During the year a series of lectures on Large Deviation Theory was given. These are currently being typed up for the Communications of DIAS, Series A (Theoretical Physics).

### 1.1.3 D. O'Connor

**Research overview**

I spent the first half of this reporting period as a visitor at the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, Canada. The Perimeter Institute (PI) was founded in 1999 with both state and private funding and is dedicated to foundational issues in current theoretical physics research. PI is still in a phase of rapid expansion with the aim of having approximately 250 theoretical physicists in residence at any one time by 2015; there are currently around 130 in residence.

The choice of theoretical physics may seem surprising from an Irish perspective, where the emphasis on "the knowledge economy" puts a strong funding bias in the direction applied and technology oriented research rather than on foundational or fundamental issues. However, the reason Canada invests so heavily in theoretical physics is based on the vision that "today's theoretical physics is tomorrow's technology". That Canada's approach will most probably be the more successful is supported by studies on the the evolution of techonology. In particular the work of W. Brian Arthur in his book textitThe Nature of Technology presents persuasive arguments that new technologies arise from deeper understanding of a natural phenomenon. Physics is the effort at understanding nature at its most fundamental level and so one can infer there should be a natural symbiosis between theoretical physics and a true knowledge economy.

The prospects for the continued success of the Canadian economy remain bright while they are prepared to put their resources into projects such as the Perimeter Institute.

The climate in which DIAS functions is unfortunately not as rosy. In 2011 we find ourselves dedicating new efforts into merely justifying our very existence, even though two consecutive external reports commended the schools research efforts and recommended that the School of Theoretical Physics expand its researcher base.

Unfortunately, both external and internal possibilities of funding postdoctoral and predoctoral researchers has largely dried up. Our hampered ablilty to take on new young researchers has knock on consequences. Though my research group has predominantly relied on external funding the current climate is making it increasingly difficult to attract the strongest candidates. In the past it was possible to secure the strongest candidates by guaranteeing them a DIAS postdoctoral position while supporting their application for external funding to come to DIAS. This is no longer possible and consequently the group has lost strong candidates who were subsequently offered external funds to work at DIAS but had at that stage accepted offers from outside of Ireland. We were, however, very fortunate to attract one outstanding new IRCSET postdoc

fellow, Mathias Ihl, who joined the group in September 2011. The very process of assessing prospective young researchers gives valuable insight into the ebb and flow of ideas in the broader theoretical physics community. If this situation continues into the future we are in serious danger of doing long term damage to the institute by demoralising those already with us and frightening off the strongest young research candidates who would join us.

I draw attention to the above in the hope that resources will be directed towards fundamental research.

**Quantum Field Theory in de Sitter Spacetime**

*"Lessons from an exactly solved interacting quantum field theory in de Sitter spacetime"*
*(D. O'Connor)*
It is argued that the correct quantization of a scalar field theory in de Sitter spacetime involves a de Sitter invariant state which is not the Bunch-Davies vacuum. A novel but natural de Sitter invariant alternative exists and it is suggested that this and is the prefered state for scalar field theories. The argument is based on the exact solution of an interacting scalar field theory.

**Fermionic lattice models**

*(C. Nash & D. O'Connor)*
An extensive study was begun of lattice fermionic systems in the presence of vortices with the intention of characterising the phase structure of such models in terms of quantities such as the amoeba of the spectral curve was commenced.

Mathias Ihl joined the group in September 2011.

## 1.2 Independent Work by Schrödinger Fellows

**String Theory Compactifications**
*(V. Braun)*

I am working on string theory compactifications. In particular, I am currently interested in computational approaches to the geometry and topology of compactification manifolds.

**Calabi-Yau Threefolds**
*(V. Braun)*

A part of my research program is to construct new Calabi-Yau threefolds (real 6-dimensional manifolds) or to investigate the existing known examples in an effort to understand which phenomena can or cannot occur. For example, I discovered [3] a Calabi-Yau manifold with the smallest known Hodge numbers $h^{1,1}(X) = h^{2,1}(X) = 1$. This manifold is seemingly simple but has various surprising features if one investigates the one-dimensional complex structure moduli space. For example, it cannot be written as a complete intersection in toric varieties.

On a seemingly related manifold, I constructed [4] a Heterotic string model that gives rise to the minimal supersymmetric standard model matter spectrum only.

**Elliptic Fibrations**
*(V. Braun)*

F-theory uses an auxiliary elliptically fibered Calabi-Yau fourfold to describe string theory in a particular regime with strong coupling. A non-Abelian gauge theory with chiral matter can arise from 7-branes on the singular locus of the base of the elliptic fibration. The codimension-one ("Kodaira") singular fibers are well understood and fall into an ADE-type classification. But at higher codimension there is much less known about possi-

bly singular fibers. For example, only last year Esole and Yau showed that some of the assumptions about codimension-two singular fibers that were made in the F-theory literature are actually wrong.

In order to better understand higher codimension singular fibers, I started [5] a program to compute the structure of the singular fibers in the largest known class of Calabi-Yau threefolds, the hypersurfaces in toric varieties. A crucial ingredient in this search was the toric varieties package for the Sage computer algebra system that I have been writing over the last few years.

**Gauge Theories**
*(S. Kovacs)*

Dr. Kovacs' research focusses on the study of the interconnections between gravity and gauge theories. He has worked on various aspects of supersymmetric gauge theories and their relations to string and M-theory in the context of the so-called AdS/CFT correspondence.

**Gauge-invariant correlation functions for $\mathcal{N} = 4$ SYM in light-cone superspace**
*(S. Kovacs, S. Ananth, & S. Parikh)*

The $\mathcal{N} = 4$ supersymmetric Yang-Mills (SYM) theory has been a major focus of investigation in the past few years because of its many remarkable properties. It possesses maximal (rigid) supersymmetry and it is a prime example of an interacting conformally invariant theory in four dimensions. This theory plays a central role in the AdS/CFT correspondence. The latter is a 'holographic' duality relating string theory in a certain manifolds to ordinary gauge theories defined on the boundary of such manifolds. The most studied and best understood example of this duality relates $\mathcal{N} = 4$ SYM to the so-called type IIB superstring theory in a background, $\mathrm{AdS}_5 \times S^5$, consisting of the direct product of a five-dimensional anti de-Sitter space and a five-sphere. A central role in this duality is played by gauge-invariant correlation functions. These are the fundamental observables in $\mathcal{N} = 4$ SYM, as in any conformal field theory, and the AdS/CFT correspondence relates them to certain scattering amplitudes in string theory.

Dr. Kovacs, in collaboration with Dr. Sudarshan Ananth and Sarthak Parikh (of the Indian Institute of Science Education and Research, Pune, India) has initiated a systematic study of correlation functions of gauge-invariant operators in $\mathcal{N} = 4$ SYM using the light-cone superspace formulation. While this formalism has a number of remarkable properties, its application to the perturbative computation of physical observables has so far been very limited. In a recent publication Dr. Kovacs and collaborators have developed techniques for the calculation of correlation functions of composite operators in configuration space. They have reproduced results in the literature for certain four-point functions of operators in the energy-momentum tensor multiplet. These results are encouraging and indicate that this approach will allow to develop efficient methods for perturbative calculations in $\mathcal{N} = 4$ SYM. Moreover the study of well defined gauge-invariant correlators provides a way to examine subtleties which may arise when computing off-shell quantities in the light-cone gauge. The elimination of non-physical degrees of freedom in the light-front quantisation leads to potential complications associated with spurious infra-red divergences. Consistency of the light-cone formulation of $\mathcal{N} = 4$ SYM – and specifically its superspace implementation – requires that such divergences be absent from gauge-invariant observables. The work of Dr. Kovacs and collaborators has shown that unphysical infra-red divergences do not appear in a class of corre-

lation functions thanks to non-trivial cancellations. Further extensions and generalisations of these results are the subject of ongoing research.

**AdS/CFT correspondence in M-theory regime**

*(S. Kovacs, H. Shimada)*

Many of the most important developments in string theory over the past fifteen years originated from the understanding of a network of dualities relating the different consistent perturbative string models. A unified picture has emerged, in which these seemingly different theories arise as limits of a more fundamental eleven-dimensional theory referred to as M-theory. Little is known about this theory at present, except that it should reduce to supergravity in the low energy limit and it should contain membranes among its fundamental degrees of freedom.

In the past few years there has been significant progress in our understanding of the dynamics of membranes in M-theory. This has opened up the possibility of extending the AdS/CFT correspondence to include examples relating M-theory in suitable backgrounds to supersymmetric gauge theories. A particularly interesting proposal was presented by Aharony, Bergman, Jafferis and Maldacena (ABJM), who suggested that M-theory in the $\mathrm{AdS}_4 \times S^7/Z_k$ space be dual to a certain Chern–Simons $\mathrm{U}(N)\times\mathrm{U}(N)$ gauge theory coupled to matter with $\mathcal{N} = 6$ supersymmetry.

Dr. Kovacs is currently working on the ABJM duality in collaboration with Dr. Hidehiko Shimada (of the Institute for Quantum Physics, Okayama, Japan). They are developing a proposal for studying this duality in a special limit which allows to probe a genuinely M-theoretic regime. This proposal relates a class of membrane configurations in the bulk to certain gauge-invariant operators in the boundary theory. On the gravitational (M-theory) side the objects considered are classical solutions corresponding to spherical membranes carrying a large angular momentum $J$. These states are conjectured to be dual to Chern–Simons operators made of $J$ scalar fields combined in a gauge-invariant way with so-called monopole operators. Describing these operators in the framework of radial quantisation leads to a correspondence between the spectrum of excitations of the spinning spherical membranes and the spectrum of scalar states carrying a total magnetic charge $J$. In the limit of large angular momentum/magnetic charge, both sides of the duality are tractable using the quasi-classical approximation and therefore explicit tests of the proposal are possible.

This is the first AdS/CFT construction in which genuine membrane excitations are identified and a precise prescription for the dual gauge theory objects is given. This study will provide important insights into the dynamics of M-theory beyond the supergravity approximation. Once the current project has been finalised and non-trivial tests of the proposal have been completed, various extensions and generalisations will be considered.

**Instantons and holography**

*(S. Kovacs)*

The AdS/CFT correspondence relating string and gauge theories is a remarkable duality for a number of reasons. One particularly interesting aspect of this duality is the fact that it relates the weak coupling limit of one theory to the strong coupling regime of the other theory. Another intriguing feature of the correspondence is its 'holographic' nature. It provides a precise relation between observables of a theory of quantum gravity (string theory) and those of an ordinary quantum field theory defined in a lower dimensional space, which can

be thought of as a 'holographic screen'.

The precise nature of the holographic relation between gauge theories and gravity has so far remained unclear. Specifically it is not understood how local properties in the bulk are encoded in the boundary theory. The study of instanton effects in the AdS/CFT correspondence provides a unique perspective on this issue. Instanton effects in the gauge theory are related to effects induced by so-called D-instantons in the dual string theory. A very precise relation between these two sources of non-perturbative effects has been established. This makes it possible to use the calculation of instanton contributions to gauge theory correlation functions to extract certain local properties of the bulk geometry and of the supergravity solution defining the dual background.

Dr. Kovacs is currently working on a research project which focusses on the application of these ideas to a class of deformations of the $\mathcal{N}$=4 SYM theory. Among these theories there are examples for which the gravitational dual is know as well as examples for which the dual geometry is unknown. One of the objectives of this work is to explicitly construct, through the analysis of instanton induced correlators in the gauge theory, the complete supergravity solution describing a dual background which has not been obtained using different techniques. Possible extensions of this project include the application of these ideas to gauge theories at finite temperature, which the AdS/CFT dictionary relates to black hole geometries.

**The Quantum Sperical Model**
*(I. Lyberg with T.C. Dorlas)*

The classical spherical model is well known. It is a model like the classical Ising model, except that the spins do not take only the values 1 and $-1$, instead

$$\sum_{j=1}^{N} \sigma_j^2 = N. \tag{1.1}$$

The partition function is thus

$$\begin{aligned} Z_N \quad &= \int_{\mathbf{R}^N} \exp(\beta J \sum_{\langle j,l \rangle} \sigma_j \sigma_l \\ &\quad + \beta H \sum_j \sigma_j) \delta(N - \sum_j \sigma_j^2) d\sigma \end{aligned} \tag{1.2}$$

In analogy to this, I have defined the partition function of the ($d$-dimensional) quantum spherical model as follows:

$$\begin{aligned} Z_N \quad = \quad & \int_{\mathbf{R}^{3N}} d^{3N}x \\ & \exp\Big(\sum_{\langle j,l \rangle} \beta z_j z_k + \sum_j \beta(Bx_j + Hz_j)\Big) \\ & \delta\left(N - \sum_k (x_k^2 + y_k^2 + z_k^2 - N)\right) \end{aligned} \tag{1.3}$$

I have found that if we have $J > 0$, $B \geq 0$ and $H > 0$, then in the limit $H \to 0$ this model has a critical point at $B = 2Jd$. In fact, ground state free energy $f_{H,\infty} := -\lim_{\beta\to\infty} \lim_{N\to\infty} (N\beta)^{-1} \log Z_N$ is in this limit

$$\lim_{H\to 0} f_{H,\infty} = -\begin{cases} J + B^2/4J, & B \leq 2Jd \\ B, & B > 2Jd. \end{cases} \tag{1.4}$$

**The quantum Toda model**
*(I. Lyberg with T.C. Dorlas)*

The periodic quantum Toda chain is a system of $N$ particles whose dynamics is described by the Hamiltonian

$$H = -\frac{1}{2}\Delta + \sum_{k=1}^{N-1} e^{x_k - x_{k+1}} + e^{x_N - x_1}, \tag{1.5}$$

where $\Delta$ is the Laplacian. In the case of only one particle the eigenvalue equation is thus

$$-\psi'' + e^x \psi = k^2 \psi. \tag{1.6}$$

It can be shown that there is a solution of (1.6) which satisfies the one particle Lippmann-Schwinger equation

$$\phi(x) = e^{ikx} - \lim_{\epsilon \downarrow 0} \int_{-\infty}^{\infty} G_0^+(x-y, (k+i\epsilon)^2) e^y \phi(y) dy, \tag{1.7}$$

where $G_0^+$ is defined as

$$G_0^+(x-y, (k+i\epsilon)^2) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{e^{i\xi|x-y|}}{\xi^2 - (k+i\epsilon)^2} d\xi \tag{1.8}$$

whenever $\epsilon > 0$. We would like to find the Lippmann-Schwinger equation corresponding to the Hamiltonian (1.5) and find a solution to the Toda equation satisfying this Lippmann-Scwinger equation. This work is still in progress.

## 1.3 Independent Work by Research Scholars and Students

**Feynman Integral**

*(M. Beau & T.C. Dorlas)*

Working with T.C. Dorlas, M. Beau's research focuses on the Feynman formulation of quantum mechanics via the concept of path integral. The problem is that the Feynman integral, allowing the computation of the propagator of the Schrödinger equation, is not well defined. Thus, they are working on developing a rigorous mathematical formulation of the Feynman integration.

In the Lagrangian formulation of quantum mechanics one defines the *action* of a particle as an integral of the Lagrangian over the time duration of the motion:

$$S(x_f, t_f; x_i, t_i) = \int_{t_i}^{t_f} dt\, L(x(t), \dot{x}(t), t).$$

In general, the Lagrangian $L(x(t), \dot{x}(t), t)$ depends explicitly on the time, as well as on the position $x(t)$ and the velocity $\dot{x}(t)$ of the particle. For one-dimensional motion, the Lagrangian has the form

$$L(x(t), \dot{x}(t), t) = \frac{m}{2}\dot{x}(t)^2 - V(x(t), t)\ ,$$

where the first term is the kinetic energy term and $V(x(t), t)$ is the external potential. The time-evolution of a wave function $\Psi(x, t)$ is then given by

$$\Psi(x_f, t_f) = \int K(x_f, t_f; x_i, t_i)\, \Psi(x_i, t_i) dx_i, \tag{1.9}$$

where the *propagator* $K(x_f, t_f; x_i, t_i)$ is given by a *path integral* of the form

$$K(x_f, t_f; x_i, t_i) = \int e^{iS(x_f, t_f; x_i, t_i)/\hbar}\, \mathcal{D}[x(t)]. \tag{1.10}$$

Here $\mathcal{D}[x(t)]$ indicates a putative "continuous product" of Lebesgue measures $\mathcal{D}[x(t)] = \prod_{t \in (t_i, t_f)} dx(t)$. (Note that the action $S$ above is a functional of the path $x(t)$.) It is a formidable mathematical challenge to make sense of this path-integral concept. Feynman himself interpreted it loosely as a limit of multidimensional integrals. However, as Erik G. F. Thomas (1999) remarks, even the finite-dimensional integrals are not proper integrals, though they can be defined as improper integrals. It was already noted by R. H. Cameron (1983) that the path integral cannot be interpreted as a complex-valued measure. In fact, as E. Thomas and F. Bijma show, it cannot even be interpreted as a summable distribution because the summability order diverges as the number of integrals tends to infinity. Various alternative approaches have been proposed to interpret the Feynman path integral as a limit of regularised integrals, e.g. R. H. Cameron and D. A. Storvick (1983), A. Truman (1979), E. Nelson (1964). The 'Eucidean approach' of 'Wick rotating' the time in the complex plane has led to the development of Euclidean quantum field theory, which

has been the most successful way of constructing examples of quantum field theories. However, this still leaves open the question as to how the path integral object should be interpreted mathematically. De Witt-Morette (1972) has argued that it should be a kind of distribution, but her approach was formal rather than constructive. The Itô-Albeverio-Høegh Krohn (1976) approach were more constructive. They gave a definition of the path integral as a map from the space of Fourier transforms of bounded measures to itself and were able to show, using a perturbation expansion, that this is well-defined for potentials which are also Fourier transforms of bounded measures. Although the latter approach assigns a clear meaning to the path integral, it is rather restrictive in that the space of Fourier transforms of bounded measures is somewhat unwieldy and more importantly, because the space of such potentials is rather small. E. Thomas initiated a different approach, with the aim of defining the path integral as a generalised type of distribution, which he called a *path distribution*. In fact, this project is at the beginning stages. He constructed an analogue of the path integral in discrete time, where the paths are sequences in a certain nuclear sequence space. M. Beau and T. Dorlas simplify his approach by defining the path distribution on a space of paths in a Hilbert space instead. This makes the construction more explicit and the technical details less demanding. Now they try to unify the different approachs of Thomas, Itô-Albeverio-Høegh Krohn and Streit-Hida (generalized Brownian functional interpretation, 1984).

**Quantum slits experiments**
*(M. Beau & T.C. Dorlas)*

The quantum mechanical problem of diffraction and interference of massive particles is discussed, though without detailed formulae, by R. P. Feynman in his famous lecture notes. A more exact treatment, though still lacking in detail, is in his book with A. R. Hibbs. The first experimental observation was made by Jönsson in 1961. Moreover, there are also experiments for neutron diffraction for single and double slits (Anton Zeilinger *et al*, 1988) and in quantum optics about optical interference, (see R. L. Pfleegor and L. Mandel, 1961).

M. Beau and T.C. Dorlas are interested in an analytic solution of the famous problem of diffraction and interference of electrons through one and two slits (for simplicity, only the one-dimensional case is considered). They study the approximative Feynman model (considering the motion in the propagation direction as a classical motion) to give some various approximations of the electron distribution which facilitate the interpretation of the results. The derivation is based on the Feynman path integral formula and this work could therefore also serve as an interesting pedagogical introduction to Feynman's formulation of quantum mechanics for university students dealing with the foundations of quantum mechanics. In addition, they try to take into account the quantum-mechanical way in all directions to solve the problem completely which has never been done and could be interesting for physicists to improve the accuracy of their experiments. In the Feynman model, they consider that the problem is separated into two motions, one between the source and the slits and the other one between the slits and the screen, which is not rigorously true since the time when the electron goes through the slit can not be determined (quantum mechanically). This is a challenging task since they have to compute the loop path corrections to the well known model.

**Bose-Einstein Condensation, & Molecules in High Magnetic Field**
*(M. Beau with V. Zagrebnov)*

M. Beau is also continuing research on other

subjects studied in his thesis, such as the generalised Bose-Einstein condensation (concept of M. van den Berg, J. Lewis and J. Pule) and its analogies with polymers (with Valentin Zagrebnov).

**Nahm's Conjecture**
*(S. Keegan)*

When is a $q$-hypergeometric series modular? This interesting open problem is far from being solved completely but a useful first step is to consider the following problem. Let $A$ be a positive-definite symmetric $r \times r$ matrix, $B$ a vector of length $r$, $C$ a scalar, each rational, and define

$$f_{A,B,C}(q) = \sum_{n=(n_1,\ldots,n_r)\in\left(\mathbb{Z}_{\geq 0}\right)^r} \frac{q^{\frac{1}{2}n^tAn+B^tn+C}}{(q)_{n_1}\ldots(q)_{n_r}}, \tag{1.11}$$

where $(q)_n = \prod_{j=1}^{n}(1-q^j)$. It is convenient to note that $f_{A,B,C}(q) = q^C f_{A,B,0}(q)$. This series converges for $|q| < 1$. Problem: describe the set of such $A$, $B$, $C$ for which (1.11) is a modular function. For $r = 1$ this problem has been solved completely by Don Zagier. A conjecture suggested by Werner Nahm attempts to partially answer the question for general $r$ by suggesting a condition the matrix $A$ must satisfy in order to guarantee the existence of $B$ and $C$ leading to modular (1.11).

In many cases Nahm's conjecture correctly predicts values of $A$ which give rise to modular $f_{A,B,C}$. However, even in such cases, there is no simple way to calculate corresponding values of $B$. The conjecture claims such values exist but gives no indication of how to compute them. Of course one could search systematically through numerous potential $B$-values, each time calculating the function $f_{A,B,C}$ and checking modularity, but this is a slow process. It would be useful to have an algorithm that directly computes $B$-values corresponding to a given matrix $A$.

Approaching the problem of modular $q$-series from the point of view of conformal field theory puts a wealth of tools at our disposal and this has been the focus of my research over the last few months, with the specific hope of understanding the behavior of the $B$-values. In the context of modularity, series of the form (1.11) first arose in the study of rational conformal field theories (RCFTs). These $f_{A,B,C}$ are expected to be RCFT characters, with the choice of $A$ determining the corresponding CFT. Mathematically RCFTs are quite well-understood and in particular there are efficient formulae for calculating their characters.

In cases where we can identify the CFT model corresponding to a particular matrix $A$, the CFT characters should be closely related to the series (1.11). For such choices of $A$, values of $B$ and $C$ can be chosen at random and the series (1.11) compared directly to characters of the corresponding CFT model. This is a fairly straightforward process as it involves numerically checking equality of $q$-series (up to a certain order), rather than the tedious process of checking modularity. For a particular choice of $B$ and $C$, if (1.11) is equal to a linear combination of CFT characters then it is necessarily modular and thus we have successfully found appropriate values of $B$ and $C$. By taking this approach we have succeeded in understanding the $B$-values in a number of special cases. We studied two different families of the matrix $A$ and in both cases successfully identified the corresponding CFT. In each case we established a clear pattern followed by the B-values. While our results are not an algorithm for computing $B$ given a general matrix $A$, they suggest that a more comprehensive search for such an algorithm may be worthwhile.

Many conformal field theory characters can be written in a form similar to (1.11) but with the addition of finite $q$-deformed binomial co-

efficients. Another interesting path for the future is to undertake a more comprehensive study of characters of this form. Such an approach may shed more light on the overlap between $q$-series and modular forms.

Recently I have also ventured into the field of solid mechanics. In collaboration with colleagues from the Department of Engineering Science, University of Oxford, I have been modeling the deformation of ductile crystalline solids by dislocation motion. Of particular interest is the inversion of experimental micro-beam Laue diffraction patterns to reveal the dislocation structures in the sample. Our current approach is to produce detailed, physically-based mechanical models which, using a diffraction post-processing routine, are then directly compared with experimental diffraction patterns. As part of this collaboration I took part in high energy transmission Laue (HETL) diffraction measurements at beamline I12 at the Diamond Light Source, Didcot, UK, in July 2011. We are currently analysing the data collected during this experimental visit and anticipate publication of the results in the coming months.

**Edge and Tunnelling Currents**
*(O. Smits)*

Olaf Smits studies the properties of edge and tunnelling currents in fractional quantum Hall systems, for single and multiple point contacts between the edges of the system. The properties of the tunnelling currents are believed to show the presence of non-Abelian anyons at conductivity 5/2, but the experimental situation is not entirely clear. Together with Joost Slingerland, Olaf derived a fluctuation-dissipation theorem which relates the noise in the tunnelling current to the noise in the edge current.

**Three-Matrix model**
*(M. Vachovski in collaboration with D. O'Connor)*

Working on the Three-Matrix model, as studied by Prof. Denjoe O'Connor and described in his paper arXiv:0806.0558v4, investigated the behaviour of various quantities such as energy, matrix eigenvalues spectrum, specific heat etc. near the phase-transition point and extracting critical exponents which characterize this transition.

**Fuzzy Scalar model**
*(M. Vachovski)*
Study of the phase diagram of non-commutative $\phi^4$ theory on a 2-sphere. With focus on the large radius limit behavior which corresponds to a scalar field on $R^3$. And with aim to localize the triple point of the phase diagram.

## 1.4 Work by Research Associates

**The Quantum Hall Effect**
*(B. Dolan & Cliff Burgess)*
Ongoing collaboration with Cliff Burgess of the Perimeter Institute, Waterloo, Canada and McMaster University University, Hamilton, Ontario, Canada on duality and the modular group in the quantum Hall effect. We are currently investigating the use of AdS/CFT correspondence techniques in condensed matter systems to describe modular symmetries in the quantum Hall effect and other strongly correlated electron systems.

**Non-commutative geometry**
*(B. Dolan, A. Balachandran, C Nash, D. O'Connor, P. Presnajder, A. Stern, K. Gupta, & R. Szabo)*

Ongoing programme to develop closed matrix algebras approximating compact manifolds, one aim of which is numerical computation.

Collaboration with Richard Szabo of Heriot-

Watt university on equivariant dimensional reduction, using fuzzy spaces as internal spaces.

**General relativity**
*(B. Dolan)*

Enthalpy and pressure in black hole thermodynamics. I have found a hitherto unknown contribution to the First Law of Black Hole Thermodynamics coming from cosmological pressure which allows for increased efficiency of a Penrose process. Work on this is ongoing.

**Monopoles, dyons and new Chern-Simons solitons**
*(D.H. Tchrakian)*
This is a review containing a substantial original component. It collects work in the construction of monopoles (and vortices) in all dimensions. New Julia-Zee type dyon like solutions in higher dimensions are also proposed. A new type of Chern–Simons densities is defined via dimensionally reduced Chern–Pontryagin densities. These occur in both odd AND even dimensional spacetimes. The numerical constructions remain to be done.

**Gravitating non-Abelian Chern–Simons solutions**
*(D.H. Tchrakian)*

This is ongoing work for the last 5 years. It was first applied to problems in AdS/CFT, in the context of both spherical and planar geometry. A particular result sought is that of thermodynamic stability of the non-Abelian black holes against the Reissner-Nordström black holes. At present, it is being applied to asymptoticall flat problems (zero comological constant), in $2+1$, $4+1$ and $6+1$ dimensional bulk. The result of thermodynamic stability of the non-Abelian black holes against the Reissner-Nordström black holes when negative comological constant is present, was discovered here too.

**Gravitating non-Abelian higher order Yang-Mills curvature solutions**
*(D.H. Tchrakian)*
This is also ongoing work. At present, it is being applied to problems in AdS/CFT, in $2+1$, $4+1$ and $6+1$ dimensional bulk. It appears that the results arrived at in the above two projects, replicate to a large extent when the Chern–Simons densities are replaced by higher order Yang-Mills curvature densities.

**Hopfions in all odd dimensional spaces**
*(D.H. Tchrakian)*
Construction of Hopf like solitons in $5+1$ dimensions in a $CP^2$ sigma model on $R^5$. These are biazimuthal solutions of 3 dimensional PDE's. Ongoing.

**Non-Abelian vortices**
*(D.H. Tchrakian)*
These are vortices on $R^2$ of the Georgi-Glashow model, and, the model where the Yang-Mills density is replaced by the non-Abelian Chern-Simons density. Further study involves the instability of the vortex in terms of the critical length in the $z-$direction.

**Solitins of NEW Chern-Simons models**
*(D.H. Tchrakian)*
The new Chern-Simons densities in terms of Yang-Mills and Higgs fields are defined in both odd and even dimensional spacetimes. The $3+1$ case has $SO(5)$ gauge group and the $2+1$ case has $SO(4)$. Ongoing.

# 2 Publications

## 2.1 Papers in refereed journals

[1] T. C. Dorlas and C. Morgan: The invalidity of a strong capacity for a quantum channel with memory, *Phys.Rev.* **A84**, 042318 (2011). July 2011.

[2] B. Dolan: Compressibility of rotating black holes, *Phys.Rev.* **D84**, 127503 (2011) (arXiv:1109.0198)

[3] B. Dolan: Pressure and volume in the first law of black hole thermodynamics, *Class. Quantum Grav.* **28**, 235017 (2011) (arXiv:1106.6260)

[4] B. Dolan: Holomorphic and anti-holomorphic conductivity flows in the quantum Hall effect, *J. Phys. A: Math. Theor.* **44**, 175001 (2011)(arXiv:1011.6641), DIAS-STP-10-12

[5] B. Dolan: The Cosmological constant and black hole thermodynamic potentials, *Class. Quant. Grav.* **28**, 125020 (2011) (arXiv:1008.5023 — The Cosmological Constant and Black Hole Equation of State, DIAS STP 10-10)

[6] B. Dolan, A. Bayntun, C. Burgess & Sung-Sik Lee: Towards a Holographic Phenomenology of Quantum Hall Experiments, *New J. Phys.* **13**, 035012 (2011) (arXiv:1008.1917)

[7] B. Kleihaus, J. Kunz, E. Radu and M. J. Rodriguez: New generalized non-spherical black hole solutions, *JHEP* **1102** 058 (2011).

[8] Y. Brihaye, E. Radu and D. H. Tchrakian: Asymptotically flat, stable black hole solutions in Einstein–Yang-Mills–Chern-Simons theory, *Phys.Rev.Lett.* **106** 071101 (2011).

[9] B. Kleihaus, J. Kunz and E. Radu: Rotating Black Holes in Dilatonic Einstein-Gauss-Bonnet Theory, *Phys.Rev.Lett.* **106** 151104 (2011).

[10] B. Kleihaus, J. Kunz, E. Radu and D. Senkbeil: Electric charge on the brane?, *Phys.Rev.D* **83** 104050 (2011).

[11] Y. Brihaye, E. Radu and D. H. Tchrakian: Einstein-Yang-Mills-Chern-Simons solutions in D=2n+1 dimensions, *Phys.Rev.D* **84** 064015 (2011).

[12] E. Radu, Y. .Shnir and D. H. Tchrakian: Scalar hairy black holes and solitons in a gravitating Goldstone model, *Phys.Lett.B* **703** 386 (2011).

[13] S. Ananth, S. Kovacs and S. Parikh: A manifestly MHV Langrangian for $\mathcal{N} = 4$ Yang–Mills, *JHEP* **1105** 051 (2011) (arXiv:1101.3540).

[14] S. Keegan, W. Nahm: Nahm's conjecture and coset models: a systematic search for matching parameters, *J. Phys. A: Math. Theor.* **44** 505204 (2011).

[15] F. Hofmann, S. keegan, A.M. Korsunsky: Analysis and diffraction post-processing of the lattice rotations and elastic strains induced by 3D dislocation loops, submitted to *Phil. Mag.*

[16] F. Hofmann, B. Abbey, L. Connor, N. Baimpas, X. Song, S. Keegan, A.M. Korsunsky: Imaging of grain level orientation and strain in thicker metallic polycrystals by high energy transmission micro-beam Laue (HETL) diffraction techniques, *Int. J. Mat. Res.* **103** (2012) pp. 192-199.

[17] V. Braun: Discrete Wilson lines in F-theory, *AHEP* 404691 (2011), [arXiv:1010.2520 (hep-th)].

[18] V. Braun: On free quotients of complete intersection Calabi-Yau manifolds, *JHEP* **04**, 005 (2011), [arXiv:1003.3235 (hep-th)].

[19] Lara B. Anderson, Volker Braun, Robert L. Karp and Burt A Ovrut: Numerical Hermitian Yang-Mills Connections and Kahler Cone Substructure, *JHEP* **01** 014 (2012), [arXiv:1103.3041 (hep-th)].

[20] S. Baessler, M. Beau, M. Kreuz, V.N. Kurlov, V.V. Nesvizhevsky, G. Pignol, K.V. Protasov, F. Vezzu, A.Yu. Voronin: The GRANIT spectrometer, *Comptes Rendus Physique* **v. 12, no. 8** (2011), pp. 707-728.

[21] D. H. Tchrakian: Notes on Yang-Mills–Higgs monopoles and dyons on $R^D$, and Chern-Simons–Higgs solitons on $R^{D-2}$: Dimensional reduction of Chern-Pontryagin densities, *J. Phys. A* **44** (2011) 343001.

[22] Yves Brihaye, Eugen Radu and D.H. Tchrakian: Instability of the Reissner-Nordström solution and new hairy black holes in d=5 dimensions, *Phys. Rev. D* **85** (2012) 044041.

[23] D. O'Connor: "Low-dimensional Yang-Mills theories: Matrix models and emergent geometry", *Teoret. Mat. Fiz.* **169, 1** (2011), pp. 49-57.

## 2.2 Papers in conference proceedings

[1] B. P. Dolan: "Enthalpy and the first law of black hole thermodynamics", Invited talk at the "Non Commutative Field Theory and Gravity" workshop of the 10th Hellenic School on Elementary Particle Physics and Gravity, Corfu, Greece, 2010. Published online in *Proceedings of Science*, (2011).

[2] B.P. Dolan: "Duality in strongly interacting systems: N = 2 SUSY Yang-Mills and the Quantum Hall Effect", Invited talk at the "Fields and Strings: Theory - Cosmology - Phenomenology" session of the 10th Hellenic School on Elementary Particle Physics and Gravity, Corfu, Greece, 2010. Published online in *Fortschritte der Physik*, July (2011).

[3] Y. Shnir and D. H. Tchrakian: "Axially-symmetric sphaleron solutions of the Skyrme model", *J. Phys. Conf. Ser.* **284**, (2011) 012053.

## 2.3 Preprints

**DIAS-STP-**

11-01 D.H. Tchrakian: Notes on Yang-Mills-Higgs monopoles and dyons on $R^D$ , and Chern - Simons - Higgs solitons on $R^(D-2)$, dimensional reduction of Chern - Pontryagin densities.

11-02 Y. Brihaye, E. Radu, and D.H. Tchrakian: Einstein-Yang-Mills-Chern-Simons solutions in *D=2n+1* dimensions.

11-03 V. Filev, D. Zoakos: Towards unquenched holographic magnetic catalysis.

11-04 T. C. Dorlas & C. Morgan: The invalidity of a strong capacity for a quantum channel with memory.

11-05 M. Beau: Feynman path integral approach to electron diffraction for one and two slits, analytical results.

11-06 Y. Brihaye, E. Radu, & D.H. Tchrakian: An instability of the

Reissner-Nordström solution and new hairy black holes in $d = 5$ dimensions.

11-07 E. Radu, Ya. Shnir, & D.H. Tchrakian: Scalar hairy black holes and solitons in a gravitating Goldstone model.

11-08 Ya Shnir & D.H. Tchrakian: Axially-symmetric sphaleron solutions of the Skyrme model.

11-09 H. Boschi-Filho, N.R.F. Braga, M.A.C. Torres, M. Ihl: Relativistic baryons in the Skyrme model revisted.

11-10 C.A. Ballon Bayona, H. Boschi-Filho, N.R.F. Braga, M. Ihl, M.A.C. Torres: Generalized baryon form factors and proton structure functions in the Sakai-Sugimoto model.

11-11 B. Dolan: Compressibility of rotating black holes.

11-12 B. Dolan: Pressure and volume in the first law of black hole thermodynamics.

11-13 V. Braun: The 24-cell and Calabi-Yau threefolds with Hodge numbers (1,1).

11-14 L.B. Anderson, V. Braun, B.A. Ovrut: Numerical Hermitian Yang-Mills connections and Kähler cone substructure.

11-15 V. Braun: Toric elliptic fibrations and f-theory compactifications.

11-16 V. Braun, P. Candelas, R. Davies & R. Donagi: The MSSM spectrum from (0,2)-deformations of the heterotic standard embedding.

11-17 E. Radu & D.H. Tchrakian: Stable black hole solutions with non-Abelian fields.

11-18 W. Nahm & S. Keegan: Integrable deformations of CFTs and the discrete Hirota equations.

11-19 E. Radu & T. Tchrakian: New Chern-Simons densities in both odd and even dimensions.

11-20 W. Nahm & S. Keegan: Nahm's conjecture and coset models: a systematic search for matching parameters.

### 2.4 Theses and other publications

[1] P. Abramski: Completeness of $\delta$-interacting particles. Ph. D. Thesis, Dublin Institute of Technology, School of Mathematical Sciences.

## 3 Programme of Scholarly Events

### 3.1 Lectures Organised by The School

- Mikhail S. Volkov (Univ. Tours, France) "Solutions in massive gravity models: Vainstein mechanisms and the ghost", 19 January.
- Carlos Herdeiro (Aveiro and Porto) "Black holes, trans-Planckian scattering and numerical relativity", 2 February.
- Per Berglund (New Hampshire) "On dS Vacua in Type IIB Flux Compactifications", 14 March.
- Cyril Levy (Copenhagen) "The Non-Commutative Integral and Spectral Triples", 15 March.
- Roman Kotecky (Warwick/Prague) "Gradiant models with non-convex potential", 5 May.
- Amihay Hanany (London) "Trivertices and SU(2)'s", 5 August.

- Volker Braun (DIAS, STP) "Introduction to Sage Mathematics Software System", 10 October.
- Matthias Ihl (DIAS, STP) "Introduction to guage/gravity correspondence and applications to holographic QCD", 10 November.
- V. B. Priezzhev (JINR, Dubna) "Return probability for the loop-erased random walk", 15 December.

### 3.2 Symposia, Conferences, Workshops organised

- **18th Irish Quantum Field Theory Meeting**, held at DIAS, 3rd-4th June.

### 3.3 Statutory Public Lecture

The Statutory Public Lecture was delivered by Professor Cumran Vafa, Donner Professor of Science, Department of Physics, Harvard University, hosted by Trinity College Dublin, held on Saturday, 19th November at 6:30 p.m. The title was *Geometric Physics*

## 4 Presentations at Conferences or Seminars

### 4.1 Talks and Papers Presented

**T.C. Dorlas:**

- Seminar talk on "Quantum channels for classical information and the strong converse" at Queen's University Belfast, 7 October.
- Talk on: "A Weakened Version of the Strong Converse for the Periodic Channel." At the CORNER summer workshop, Cambridge, 21-22 July.
- Expository talks (6) at the Summer school on "Algebra, Geometry, and Mathematical Physics" (AGMP11) in Tjärnö, Sweden, 6-9 September. Title: *The magnetisation of the transverse-field Ising model.*
- Seminar talk at Chalmers University, Göteborg, Sweden, 2 September. Title: *The strong converse of the channel coding theorem and a modification for the periodic quantum channel.*
- Seminar talk at Chalmers University, Göteborg, Sweden, 9 December.

**D. O'Connor:**

- Talk "Stability of Kitaev Trivalent Models", Quantum Information and Condensed Matter Physics, Maynooth, 9 September.
- Talk "Regulating Field Theories using Matrix Models", Syracuse University, USA, Balfest, 30 November-5 December.

**V. Braun:**

- Talk: String Theory Seminar, Oxford University, UK, 14 February, "Calabi-Yau Threefolds with Hodge Numbers h11=h21=1".
- Talk: Max Kreuzer Memorial, Erwin Schroedinger Institute, Vienna, Austria, 26 June, "Calabi-Yau Threefolds with Large and with Small Hodge Numbers".
- Talk: CMS meeting, University of Edmonton, Alberta, Canada, 3 June, "Toric Geometry and Sage".
- Talk: Seminar, University of Marseilles, 14 November, "Explicit Solutions for String Compactifications".

**M. Beau:**

- Presentation to Governing Board of DIAS on "Feynman Path Integral approach to electron diffraction for one and two slits: analytical results", 9 November.

**S. Kovacs:**

- Seminar: Trinity College Dublin, Ireland, 31 January and 07 February, "A manifestly MHV Lagrangian for $\mathcal{N} = 4$ Yang–Mills".

- Seminar: Department of Physics, University of Rome "Tor Vergata", Italy, 19 December, "Bulk geometry form instanton calculus".

- Seminar: Department of Physics, University of Rome "Tor Vergata", Italy, 20 December, "M-theoretic $AdS_4/CFT_3$".

- Talk: Indian Institute of Science Education and Research, Pune, India, 27 February, "Instantons and holography".

**M. Vachovski**

- Talk: EU-NCG Annual Meeting in Bucharest, 25 April, "Critical Exponents in Matrix Models".

**T. Kaltenbrunner**

- Talk: EU-NCG meeting, Bucharest, 25 April, "Application of the Wang-Landau Algorithm to the 3-Matrix-Model"

# 5 Collaboration with the Wider Research Community

## 5.1 Lecture Courses, Conferences and Workshops

### 5.1.1 International

**T. Dorlas:**

- Speaker at the Summer School on "Algebra, Geometry and Mathematical Physics", Tjärnö, Sweden, 5-10 September. Lectures on "Quantum mechanics and the Bethe Ansatz."

**V. Braun:**

- Taught intensive mini course on "Toric Geometry and Sage" at LMU, Munich, Germany, 26-29 April.

### 5.1.2 National

**S. Kovacs:**

- Courses taught: Classical Mechanics I & II (MA1241 & MA1242) for Junior Freshman Mathematics and Theoretical Physics students, Trinity College Dublin, Academic Years 2010/2011 and 2011/2012.

**I. Lyberg**

- Taught course on the Weyl group. The purpose of the course was to show the equivalence between the quotient group definition of the Weyl group and the reflection group definition.

**S. Keegan**

- Taught course module on Financial Mathematics to 3rd year undergraduate mathematics students and postgraduate higher diploma student at the School of Mathematics, University College Dublin from September-December.

**M. Beau**

- textitFriday Afternoon Seminar, School of Theoretical Physics, DIAS. Three lectures on: "How to compute the Feynman propagator for the delta-function potential using Feynman paths integral¿', January-February.

- textitFriday Afternoon Seminar, School of Theoretical Physics, DIAS. Three lectures on: "Feynman Integral and Slits experiments", June.

- textitFriday Afternoon Seminar, School of Theoretical Physics, DIAS. Five lectures on: "Theory of representation of Lie groups/Lie algebras", September-October.

## 5.2 Staff Acting as External Supervisors

**T.C. Dorlas:**

- Ph.D. supervisor for Pavel Ambramski (DIT, School of Mathematical Sciences).

**D. O'Connor:**

- Ph.D. supervisor for Thomas Kaltenbrunner (NUI Maynooth), funded by the EU-NCG Network.

- Ph.D. supervisor for Martin Vachovski (NUI Maynooth), funded by the EU-NCG Network.

**S. Keegan:**

- Supervised a transition year student, Aoife Gregg, who spent one week on a work experience placement in the School of Theoretical Physics. Aoife spent this week digitising the "Communications of the Dublin Institute for Advanced Studies".

- Supervised the research project Aoife Gregg entered for the BT Young Scientist and Technology Exhibition 2012. She undertook a frequency analysis of the Irish language and used this analysis as a method of dating Irish manuscripts. Her project "Cryptography: a study of the Irish language" was awarded the overall runner-up prize as well as the Intel student award.

## 5.3 Staff Acting as External Examiners

**W. Nahm:**

- External examiner for

**T. Dorlas:**

- External examiner for the confirmation examination of Carlos Argaez at D.I.T., 29 September. Title of thesis: "Solutions to quasi-relativistic multiconfigurative Hartree-Fock equations in Quantum Chemistry."

**D. O'Connor:**

- External advisor to the Graduate Program in Theoretical Physics, Annaba University Algeria.

## 5.4 Speakers Sponsored at Outside Conferences/Meetings

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## 5.5 Research Associates

- AT&T: N. Duffield
- BM Annaba University: B. Ydri
- DCU: E. Buffet, J. Burzlaff, E. O'Riordan
- DIT: D. Gilbert, M. Golden, B. Goldsmith, P. Houston, E. Prodanov
- ICTP, Trieste : J. Chela-Flores
- IT, Athlone: M. Daly
- IT, Carlow: D. O Sé
- IT, Tallaght: N. Gorman
- Ludwig-Maximilians-Universität München: I. Sachs
- Meteorological Service: P. Lynch
- NUI, Cork: M. Vandyck
- NUI, Galway: J. Burns, M.P. Tuite
- NUI, Maynooth: B. Dolan, D. Heffernan, C. Nash, A. O'Farrell, J. Slingerland, J. Vala, P. Watts
- Open University: A.I. Solomon
- Oxford University: R.G. Flood
- TCD: P.S. Florides, J. Miller, D. Weaire
- Universiteit Leiden: F. Freire
- UCD: A. Ottewill, J.V. Pulé, W. Sullivan
- UL: S. O'Brien
- University Warwick: N. O'Connell
- Unaffiliated: T. Garavaglia, M. Leitner, G.M. O'Brien, D. Ó Mathuna, J.A. Slevin, D.H. Tchrakian

## 5.6 International

### 5.6.1 Visiting Researchers

*Short visits (up to one week):*

- Michael Volklov (Univ. of Tours, France), 17-21 January, 2-5 June.
- Carlos Herdeira (Universidade de Aveiro, Portugal), 1-4 February.
- Francisco Navarro Lerida (University of Madrid, Spain), 20-26 February.
- Cyril Levy (University of Copenhagen, Denmark), 15-21 March.
- Baptiste Savoie (CPT University of Aix Marseilles, France), 8-11 April.
- Idrish Huet Hernandez (TPI, Friedrich-Schiller Universitat, Germany), 7-19 April.
- Yves Brihaye (Universite of Mons, Belgium), 30 January-3 February, 13 April.
- Per Berglund (University of New Hampshire), 14-17 March.
- Roman Kotecky (University of Warwick, U.K.), 1-7 May.
- Olaf Lechtenfeld (Leibniz University, Hannover, Germany), 29 May-4 June.
- Jutta Kunz (Universitat Oldenburg, Germany), 31 May-5 June.
- Patrick Dorey (Durham University, U.K.), 2-5 June.

- Andreas Wipf (Jena University, Germany), 2-5 June.
- Anne Tasmine (Durham University, U.K.), 1-5 June.
- Sinead Keegan (DIAS and Oxford, U.K.), 1-5 June.
- V.B. Priezzhev (Joint Institute for Nuclear Research, Moscow, Russia) 11-17 December.

*Long visits:*

- Ruben Manvelyan (Yerevan Physics Institute, Armenia) 2-22 March
- Yakov Shnir (University of Durham, U.K.) 27 May-10 June.
- R.F. O'Connell (Louisiana State University, U.S.A.) 28 June-5 August.

### 5.6.2 Research Visits by School Staff

**W. Nahm:**

- Research visit to Mathematics Department, Université Lille 1, July.
- Research visit to Max-Planck-Institute for Mathematics, Bonn, 23-30 August.

**T.C. Dorlas:**

- Visit to Cambridge University, 21-23 November.
- Visit to Chalmers University, Göteborg, Sweden, 6-9 December.

**D. O'Connor:**

- Visit to Perimeter Institute, Canada January-July.
- Visit to Syracuse University, USA, 30 November-5 December.

**V. Braun:**

- Visit to University of Pennsylvania, Philadelphia, USA, 14-30 January.
- Visit to University of Pennsylvania, Philadelphia, USA, 26 March to 12 April.

**S. Keegan:**

- Research visit to Diamond Light Source, Diamond, UK, July.

**S. Kovacs:**

- Visit to Indian Institute of Science Education and Research, Pune, India, 23 February-7 March.
- Visit to Department of Physics, University of Rome "Tor Vergata", Rome, Italy, 19-30 December.

### 5.6.3 Research Collaboration

**D.H. Tchrakian**

- Collaboration with Peter Breitenlohner, Max-Planck, Munich, Germany.
- Collaboration with Yves Brihaye, U. Mons, Belgium.
- Collaboration with Ruben Manvelyan, Yerevan, Armenia.
- Collaboration with Francisco Navarro-Lerida, U. Compultense, Madrid, Spain.
- Collaboration with Jürgen Burzlaff, DCU, Ireland.

# 6 Participation in Outside Committees

**W. Nahm:**

- Chair, Research Subcommittee of the Mathematics Committee, Royal Irish Academy.

**T.C. Dorlas:**

- Thesis supervisor for Pavel Abramski, who completed his thesis in November, entitled: "Completeness of $\delta$-interacting Particles". He was examined on 12 December 2001 and passed subject to minor corrections.

**D. O'Connor:**

- Member of the International Advisory Board of the Central European Joint Programme of Doctoral Studies in Theoretical Physics.

**B. Dolan:**

- Refereed eight articles for: NPB; PRL; PRD; JHEP; Physical Review Letters; Physical Review D; European Physics Journal C; Symmetry, Integrability and Geometry: Methods and Applications (SIGMA); Physica A.

# 7 MEMBERSHIP OF PROFESSIONAL ASSOCIATIONS

**T.C. Dorlas:**

- Member of: IAMP, AMS, WG, NNV.

**B. Dolan:**

- Editor of: Nature, Physics Section: Scientific Reports.

# 8 Attendance at External Conferences, Workshops, Meetings and Lectures

## 8.1 Conferences/Workshops/ Scientific Meetings Attended

**T.C. Dorlas:**

- "Biannual meeting on Statistical Mechanics", Rutgers University, New Jersey, USA, 9-11 May.
- Cambridge Summer Workshop on "Quantum Information Theory with Correlated Resources", 21-22 July.

**D. O'Connor:**

- "Regulating Quantum Field Theory with Matrix Models", Colloquium, Perimeter Institute, Canada, 9 March.
- "Lessons from an exactly solved interacting quantum field theory in de Sitter spacetime", Perimeter Institute, Canada, 28 June.
- "Stability of Kitaev Trivalent Models", Maynooth, 9 September.
- "Kitaev Spin models and their phase diagrams", Syracuse University, 2 December.
- "Regulating Field Theories using Matrix Models", Syracuse University, USA, 3 December.

**M. Beau:**

- "Mathematical Topics in Quantum Mechanics and Quantum Information, Tjärnö, Sweden, 4-10 September.

**V. Braun:**

- Workshop "Sage Days 27", University of Washington, Seattle, USA, 7-13 January.
- Conference "Extremal metrics: evolution equations and stability", Centre International de Rencontres Mathématiques, Marseille, France, 7-10 Feb.
- Conference "New Geometric and Non-Geometric Vacua in String Theory", Imperial College, London, 11-13 February.
- Workshop "Sage Days 29", University of Washington, Seattle, USA, 20-25 March.
- Workshop of the String Vacuum Project, University of Pennsylvania, Philadelphia, USA, 23-25 May.
- Computational Toric Geometry at the CMS meeting, University of Edmonton, Alberta, Canada, 3-4 June.
- Workshop "Sage Days 31", University of Washington, Seattle, USA, 13-17 June.
- Max Kreuzer Memorial Conference, Erwin Schroedinger Institute, Vienna, Austria, 25-28 June.
- String Theory conference, Benasque, Spain, 3-15 July.
- Simons Workshop, Stony Brook University, USA, 10-19 August.
- Workshop "Sage Days 32", University of Washington, Seattle, USA, 21-25 August.
- Workshop "Sage-Singular Days", University of Kaiserslautern, Germany, 26-30 December.

**B. Dolan:**

- Bayrischzell Workshop, "Noncommutativity and Physics: Spacetime Quantum Geometry", Bayrischzell, 20-23 May.
- "Supersymmetry in Integrable Systems (SIS'11)", International Workshop, 01-04 August, Hannover, Germany.

**T. Kaltenbrunner:**

- Cosmology and K-Theory, Cardiff, 2-10 February.
- Workshop on QFT, Cardiff, 18-21 April.
- EU-NCG Meeting, Bucharest, 24-30 April.
- Workshop on TFT + Categorification, Cardiff, 8-11 May.

**S. Keegan:**

- "Mathematics Teaching Matters", 4th Conference on Research in Mathematics Education (MEI 4), St. Patrick's College, September.

**S. Kovacs:**

- "Quantum Field Theory 2011", Indian Institute of Science Education and Research, Pune, India, 23-27 February.
- "Quantum Integrability and Gauge Theories", Trinity College Dublin, Ireland, 28 March-2 April.
- "18th Irish Quantum Field Theory Meeting", Dublin Institute for Advanced Studies, Ireland, 3-4 June.

**I. Lyberg**

- Summer School on "Algebra, Geometry and Mathematical Physics", Tjärnö, Sweden, organised by the University of Gothenburg, 5-9 September.

**M. Vachovski:**

- "EU-NCG Annual Meeting", Bucharest, Romania, 25-30 April.
- "Noncommutativity and Physics: Spacetime Quantum Geometry", Bayrischzell, Germany, 20-23 May.
- "Annual Theory Meeting", IPPP, Durham, GB, 15-17 December.

**T. Kaltenbrunner:**

- "Cosmology and K-Theory", Cardiff, 3-10 February.
- "Workshop on QFT", Cardiff, 18-21 April.
- "EU-NCG Meeting", Bucharest, 24-30 April.
- "Workshop on TFT + Categorification", Cardiff, 8-11 May.

### 8.2 Lectures and Organisational Meetings Attended

**T. Kaltenbrunner**

- M. Atiyah: "Geometry and Physics: Past, Present and Future", Cardiff, 17 January.

## 9 Research Grants/External Funds Secured

**D. O'Connor:**

- 2007-2011: Node of Marie Curie Research Training Network *e* 233652.73.
- 2011-2013: An Embark Initative Postdoctoral Fellowship to Matthias Ihl funded by IRCSET for a period of two years with effect from 1 September 2011.
- 2010-2012: An INSPIRE Initiative Postdoctoral Fellowship to Veselin Filev funded by IRCSET and Marie Curie.
- 2009-2011: Marie Curie Early Stage Research Fellowship to T. Kaltenbrunner, MRTN-CT-2006-031962
- 2009-2011: Marie Curie Early Stage Research Fellowship to M. Vachovski, MRTN-CT-2006-031962

**D.H. Tchrakian**

- Project RFO07-330PHY of the SFI.

## 10 Honours/Awards/ Special Achievements Received

**W. Nahm**

- Elected to the Fellowship of the Royal Society on 19 May.

## 11 Public Awareness Initiatives And Activities Undertaken

### 11.1 Public Lectures

**B. Dolan:**

- Nature through the looking glass, talk at Maynooth Ignite series, NUI Maynooth, 22 December.

- Contributed, in an advisory capacity, to "Dublin By Numb3rs", a mathematical guided tour of Dublin, primarily aimed at school children.